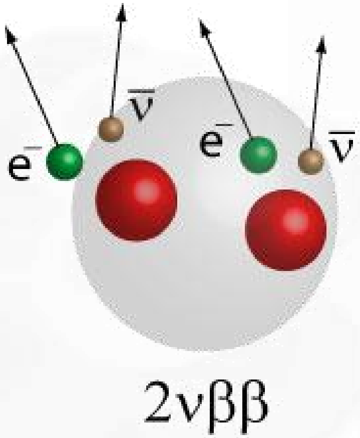
Bolometric experiments with particle identification for $0\nu2\beta$ decay search: CUPID framework

Anastasiia Zolotarova

Double Beta Decay

Two neutrino 2β decay
Allowed by SM:

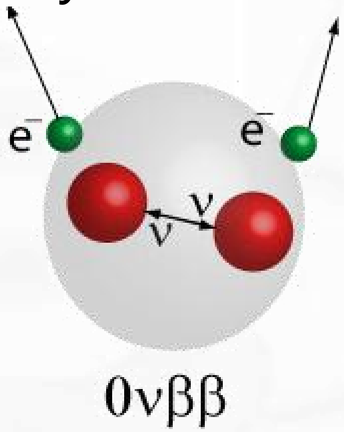


$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\upsilon_e}$$

- The rarest observed nuclear decay
- Information about nuclear matrix elements → test the theoretical description

$T_{1/2}$ (2ν2β) ~ 10^{18}-10^{24} years

Neutrinoless 2β decay
Beyond the SM:



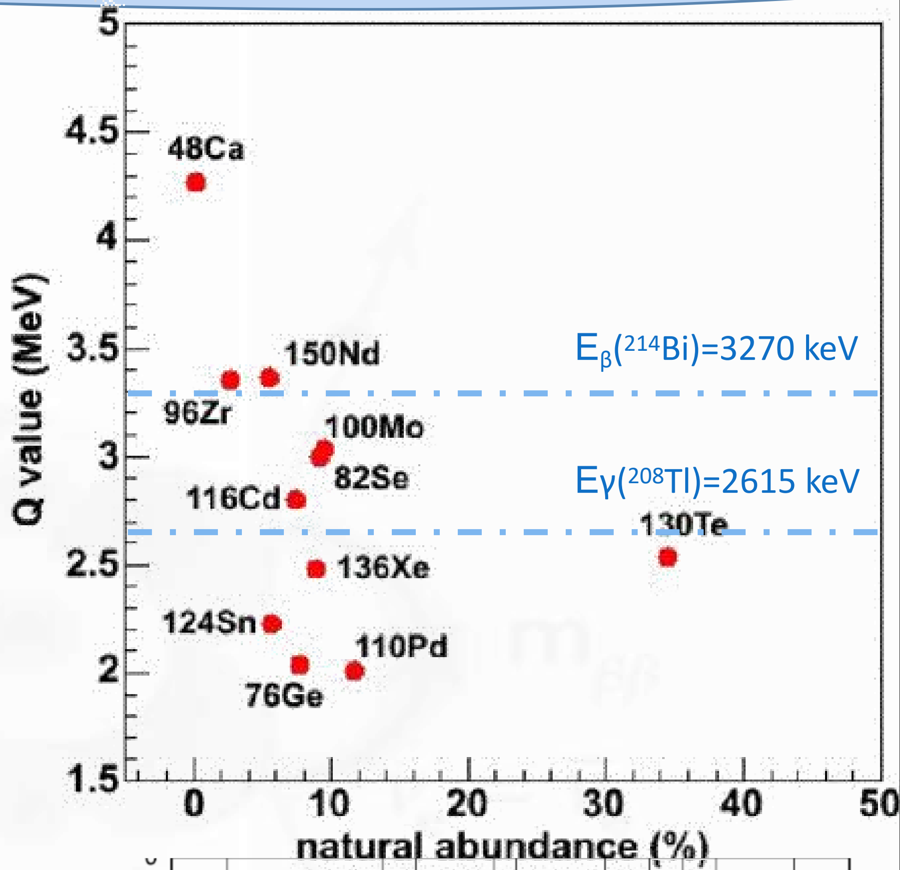
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

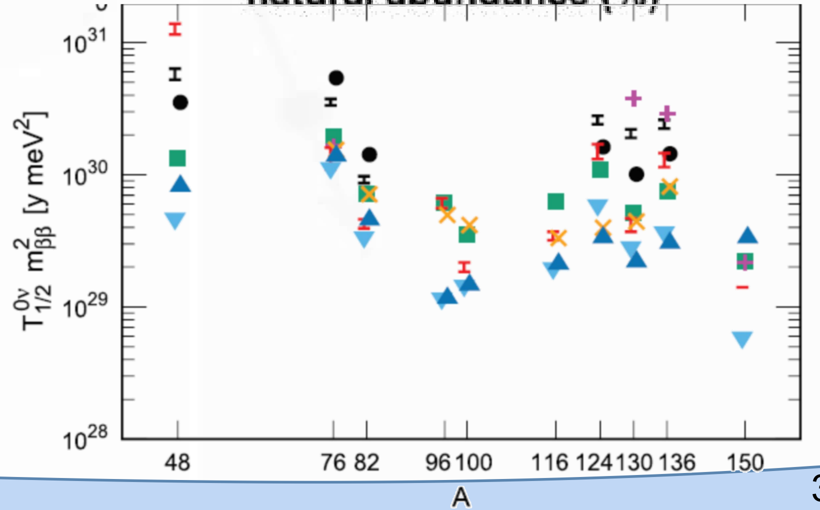
If observed:

- Majorana nature of neutrino
- Lepton number violation: ΔL=2
- Absolute neutrino mass scale determination and information about the mass hierarchy
- $T_{1/2}$ (0ν2β) > 10^{24} -10^{26} years

0ν2β decay candidates

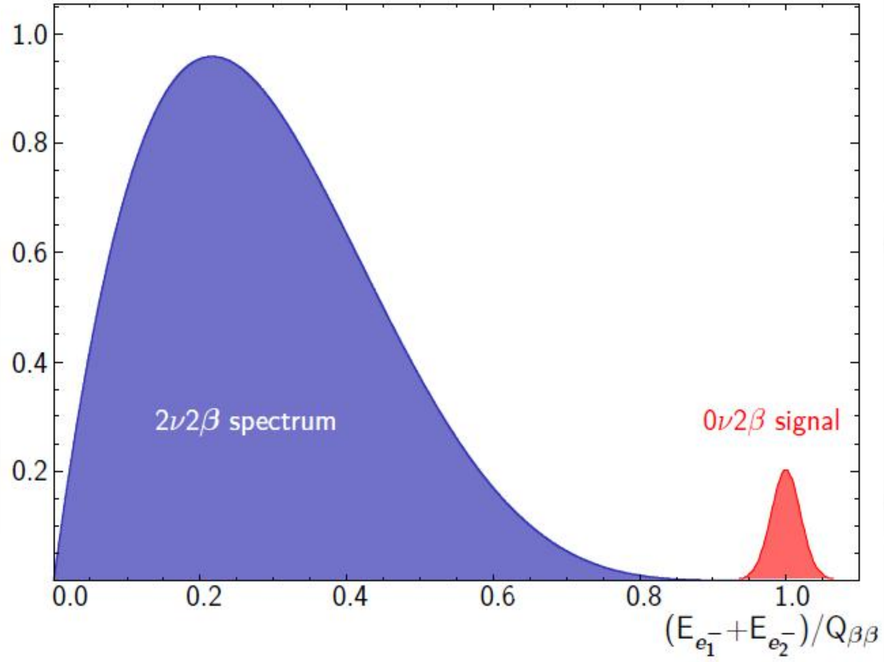
- Even-even nuclei, β decay energetically forbidden or strongly suppressed
- Allowed in 35 nuclei
- Few are interesting for experiments
- Isotopic abundance is highly important
- Q-value is significant for background level in ROI





Experimental signature

Sum energy spectrum of 2β decay:



$$T_{1/2}^{0\upsilon2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a – isotopic abundance

ϵ – detection efficiency

M – source mass

t – exposure time

b – background index at ROI

δE – energy resolution at ROI

In case of zero-bkg: $T_{1/2}^{0\upsilon2\beta} \propto a \cdot \epsilon \cdot M \cdot t$

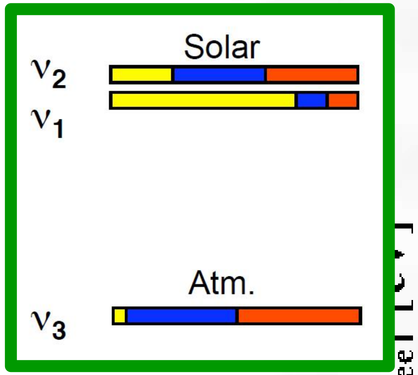
«Zero-background» ton-scale experiment
with high energy resolution (~ 0.2%):
b ≤10^{-4} c/(keV×kg×y)

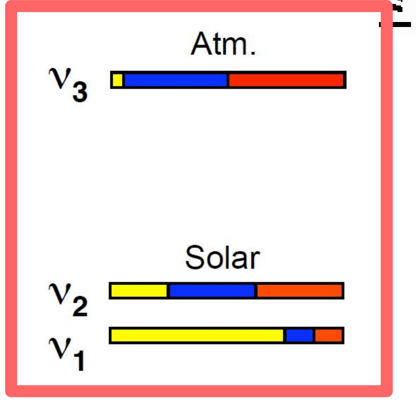
Investigation of neutrino mass hierarchy

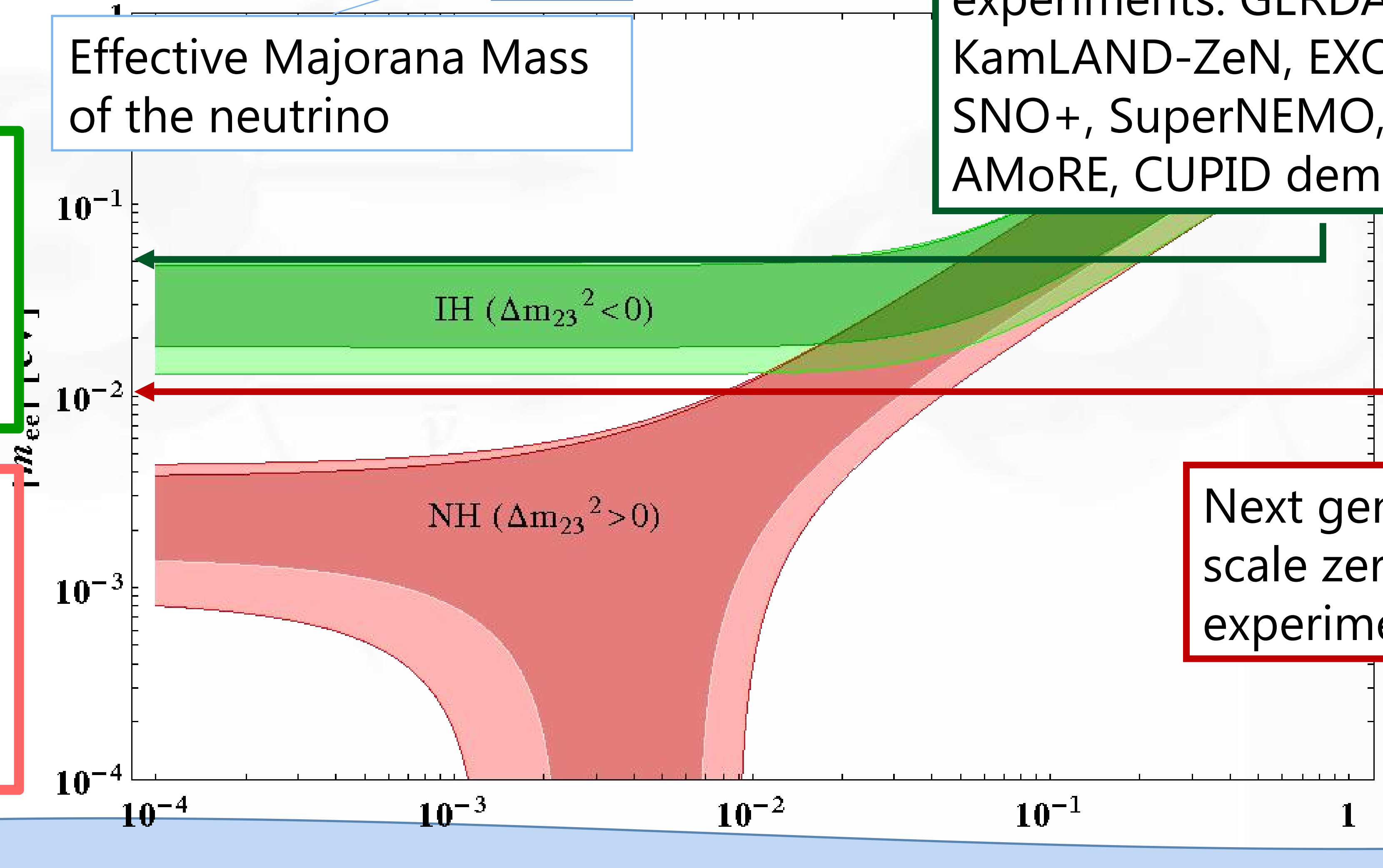
$$(T_{1/2}^{0\upsilon 2\beta})^{-1} = G(Q,Z)g_A^4|NME|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana Mass of the neutrino

Current and near future experiments: GERDA, Majorana, KamLAND-ZeN, EXO, CUORE, SNO+, SuperNEMO, NEXT, AMoRE, CUPID demonstrators



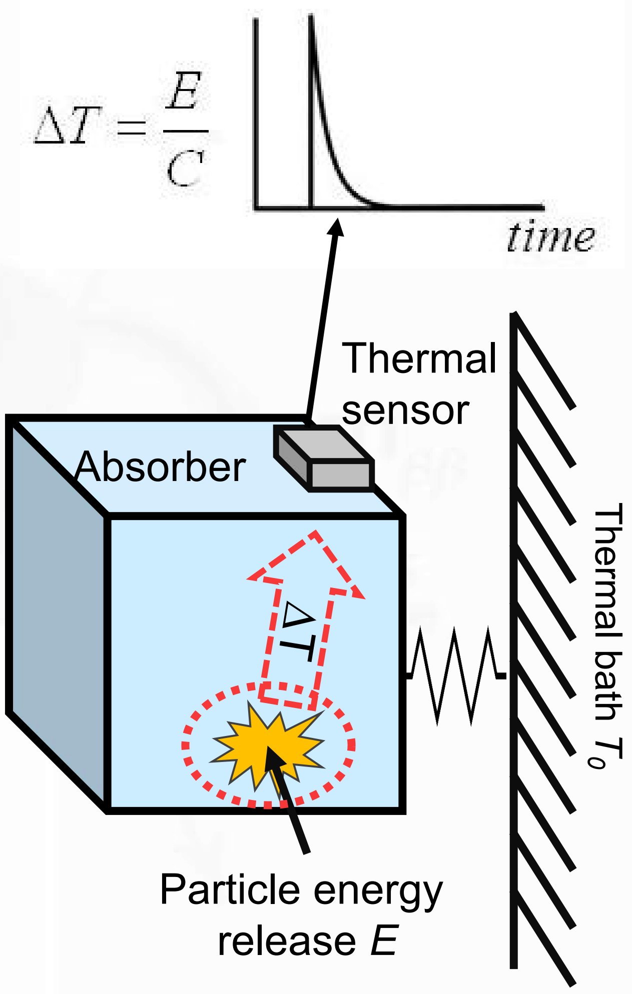




Next generation: ton-scale zero-background experiments

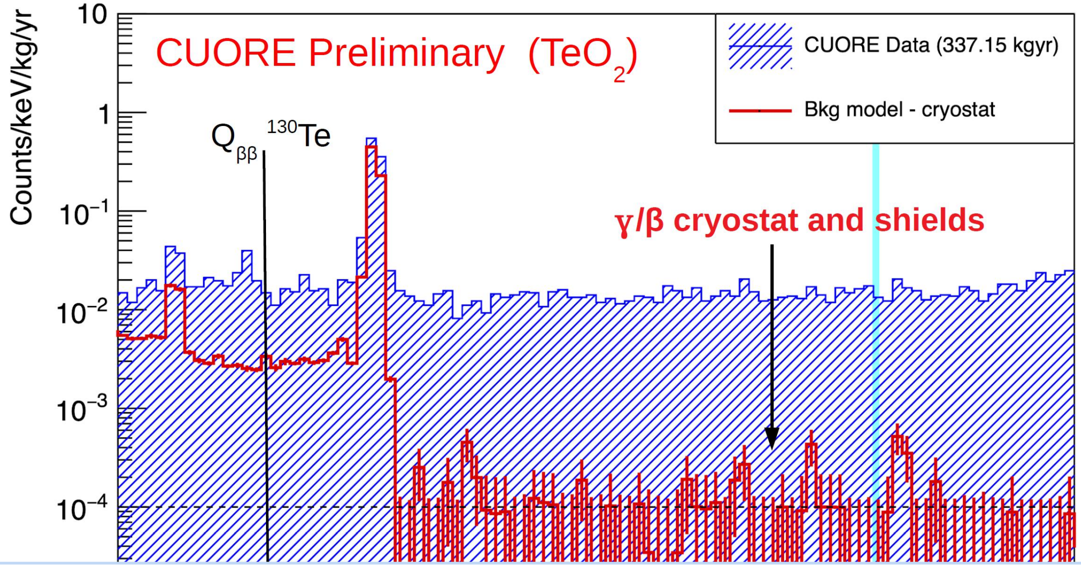
Bolometric technique

- Source is embedded in a crystal → **High detection efficiency**
- 0.1-0.5 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%)** in the ROI

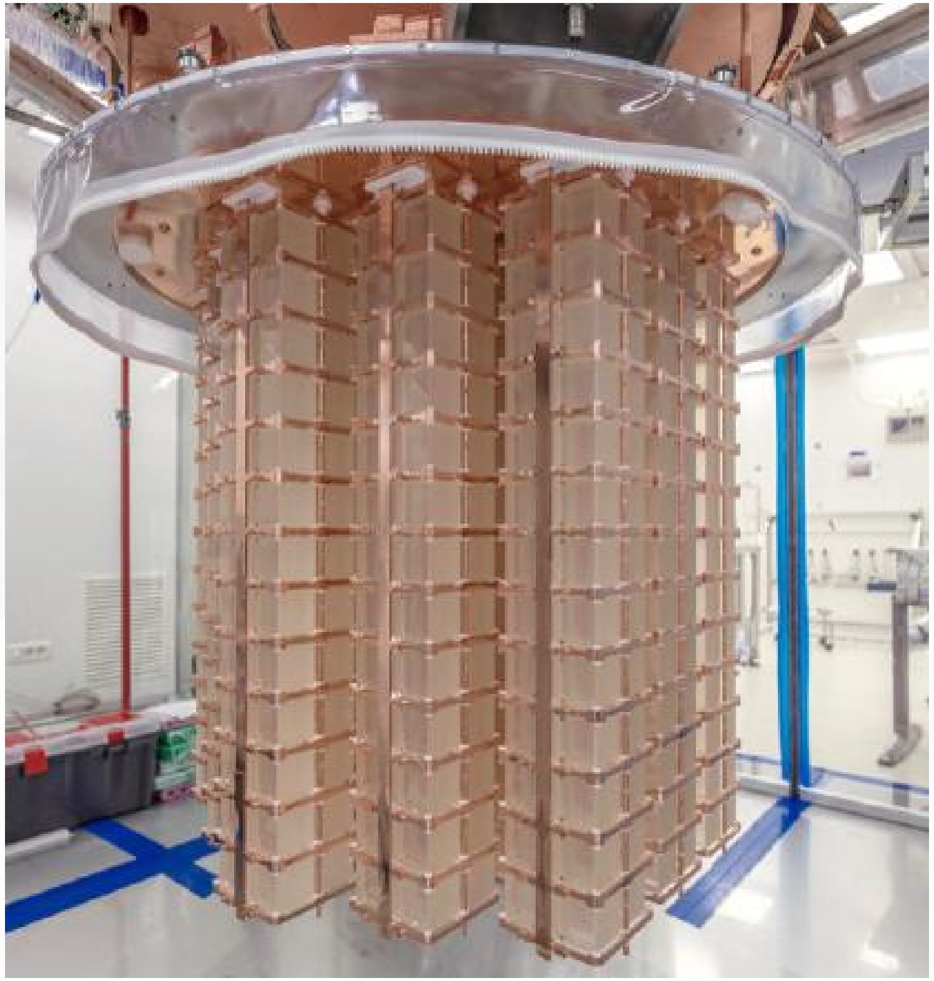


CUORE experiment

- **CUORE**: Cryogenic Underground Observatory for Rare Events: the first cryogenic **ton-scale 0ν2β experiment** (988×0.75 kg TeO_2 bolometers)



There is irreducible background due to **alpha particles**, emitted at the **surfaces** and energy-degraded



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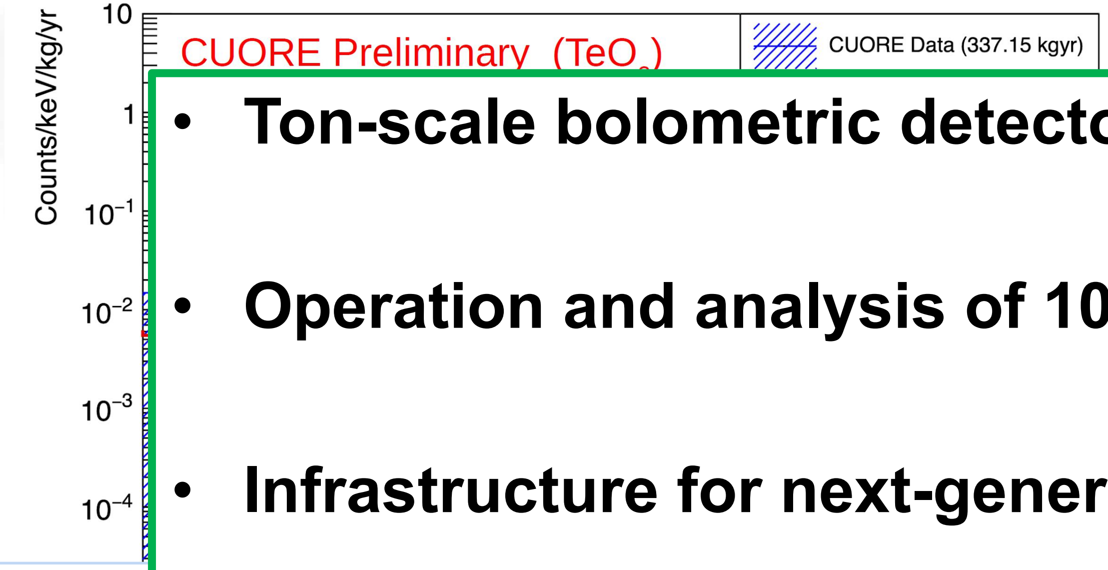
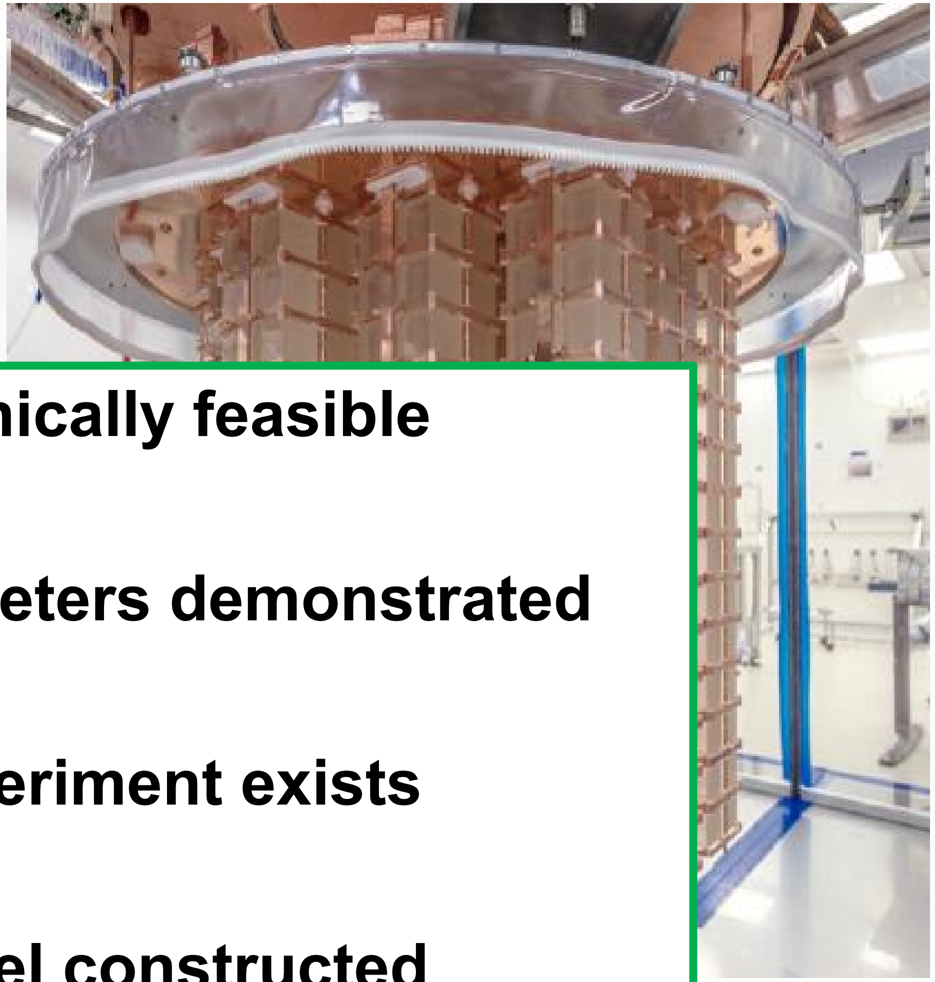


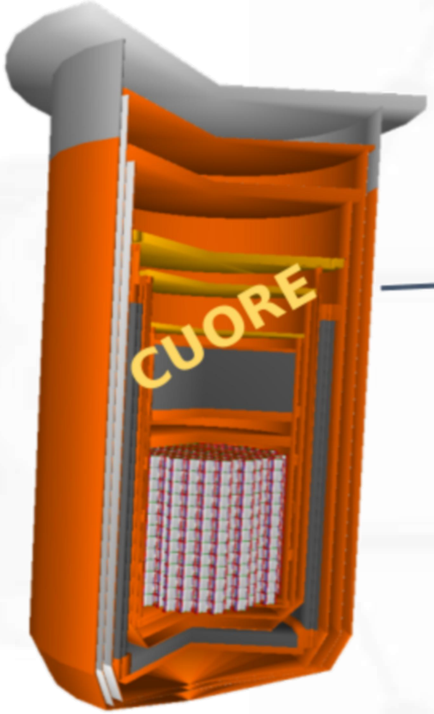
The
par

- **Ton-scale bolometric detector is technically feasible**
- **Operation and analysis of 1000 bolometers demonstrated**
- **Infrastructure for next-generation experiment exists**
- **Reliable data-driven background model constructed**



CUPID (CUORE Upgrade with Particle IDentification)

Follow-up using CUORE facility with background improved by a factor 100



Best world limit on ^{130}Te
$T_{1/2}^{0\nu} > 3.2 \times 10^{25}$ y @90% CI
PRL 124, 122501 (2020)

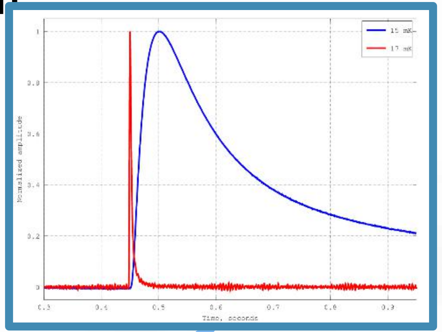
7 countries
~180 members

Best world limit on ^{100}Mo
$T_{1/2}^{0\nu} > 1.4 \times 10^{24}$ y @90% CI
Neutrino2020, poster #419
PRL to be submitted

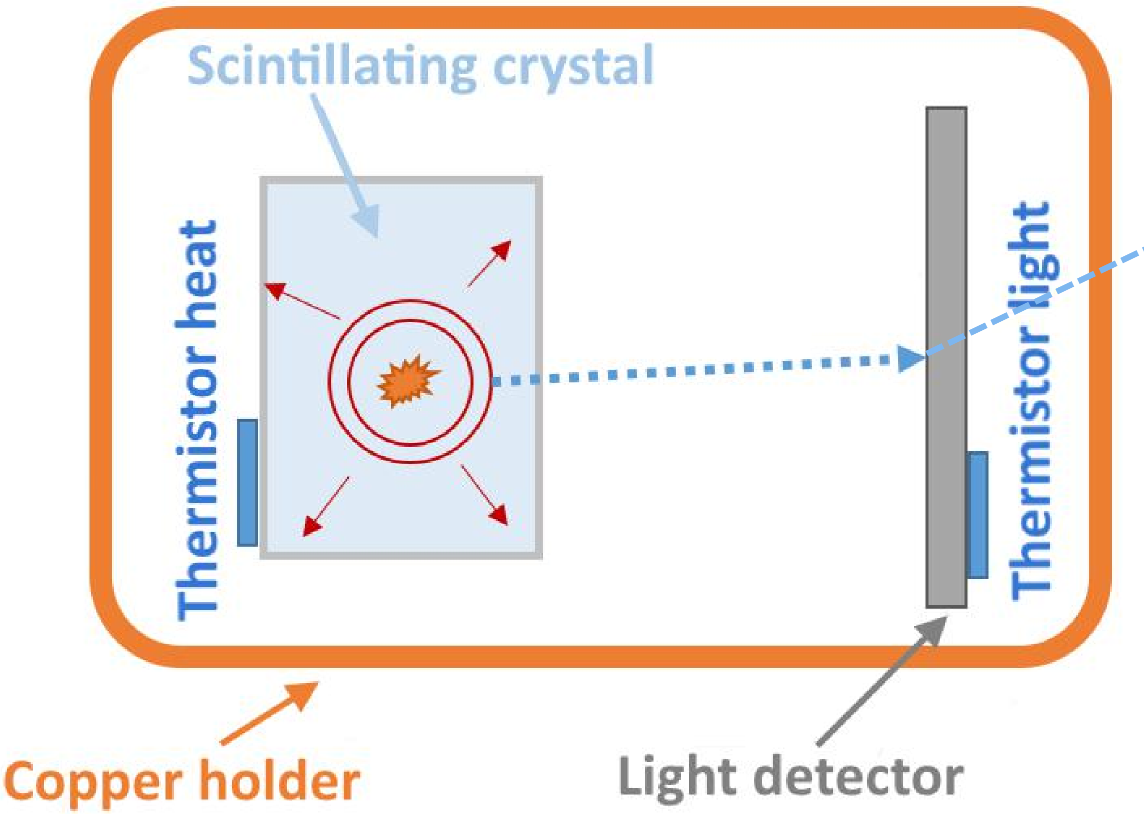
Best world limit on ^{82}Se
$T_{1/2}^{0\nu} > 3.5 \times 10^{24}$ y @90% CI
PRL 123, 032501 (2019)

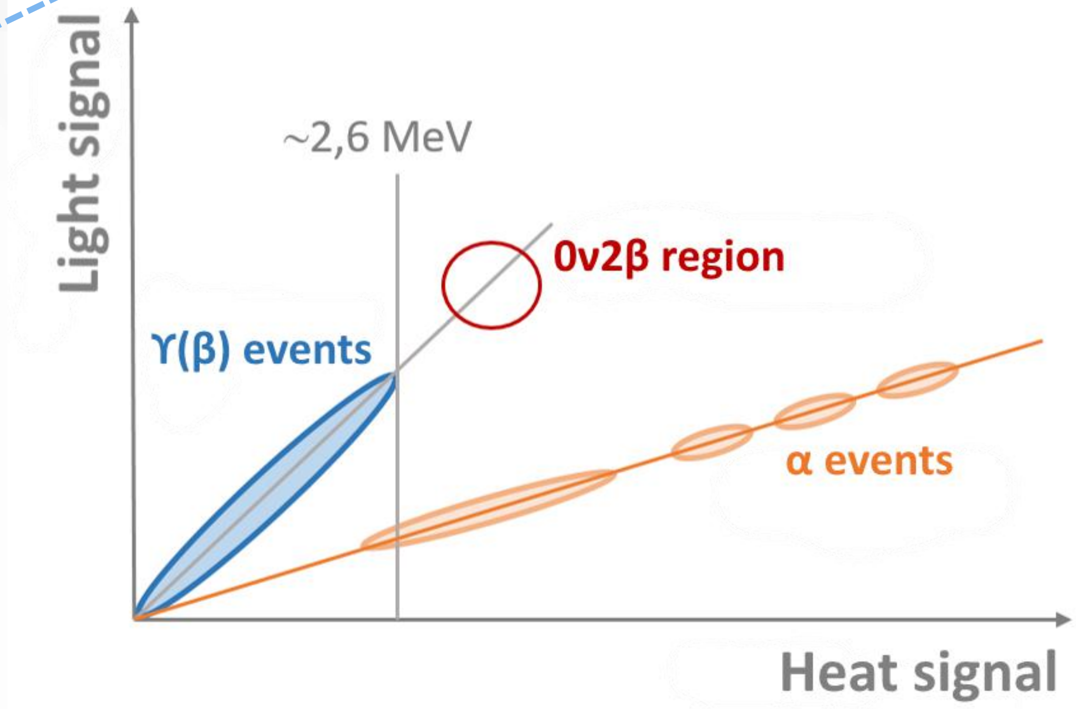
Scintillating bolometers

- Scintillator →Particle discrimination using light:
  >99.9 α background rejection



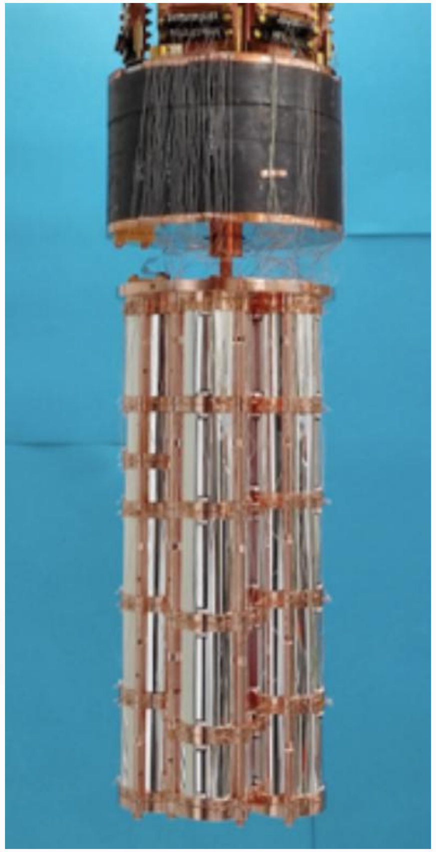
Typical signal**: 0.1 mK / MeV**,
converted to **0.1-0.5 mV / MeV**

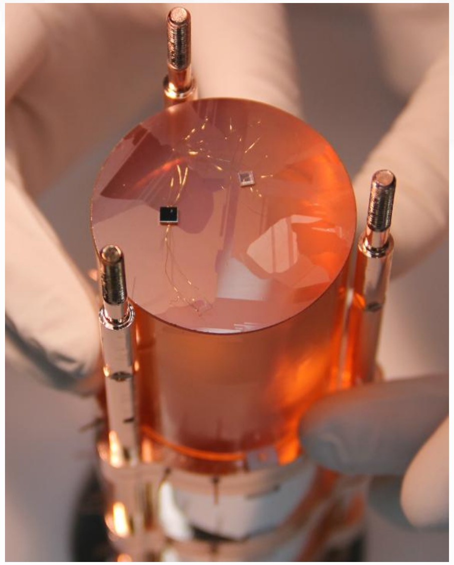


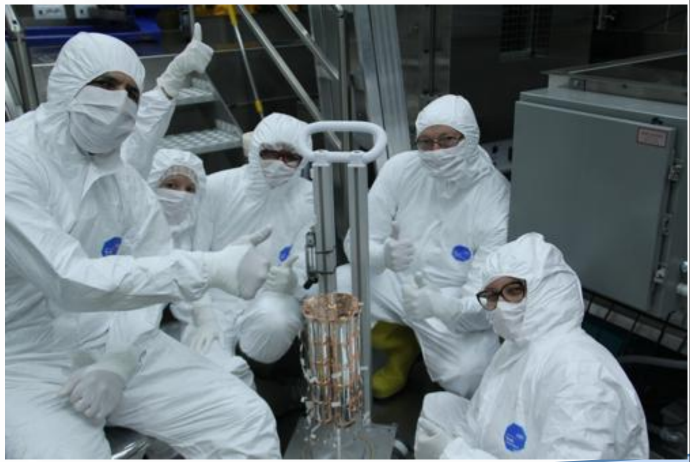


CUPID-0 demonstrator (^{82}Se)

- The first array of scintillating bolometers for the investigation of ^{82}Se 0ν2β in LNGS
- ^{82}Se $Q_{\beta\beta}$=2998 keV
- 95% enriched Zn^{82}Se bolometers (5.17 kg of ^{82}Se)
- 26 bolometers (24 enr + 2 nat)+31 Ge LD arranged in 5 towers



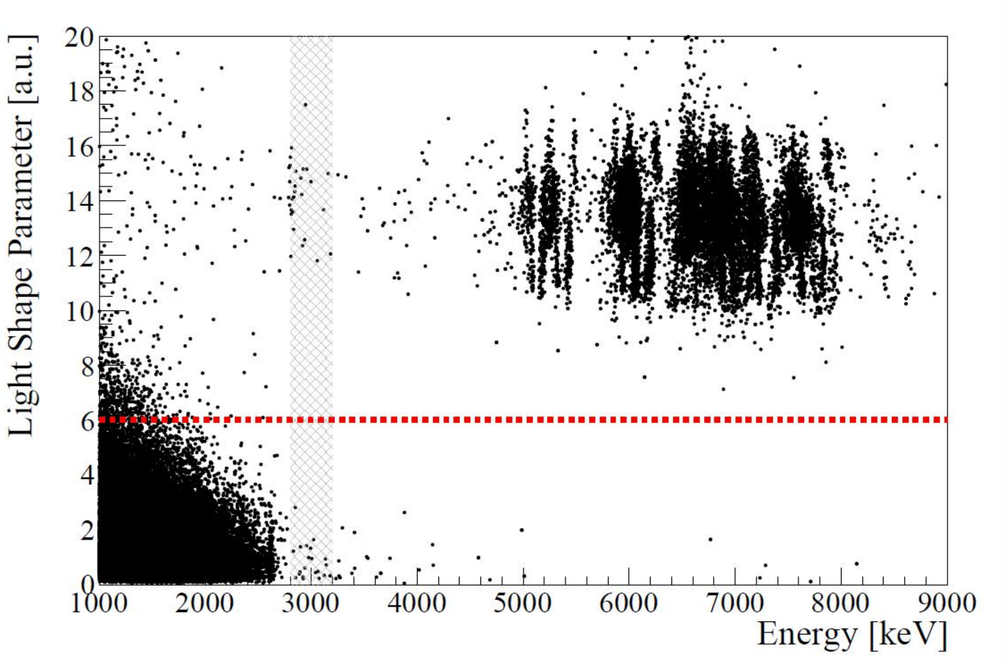


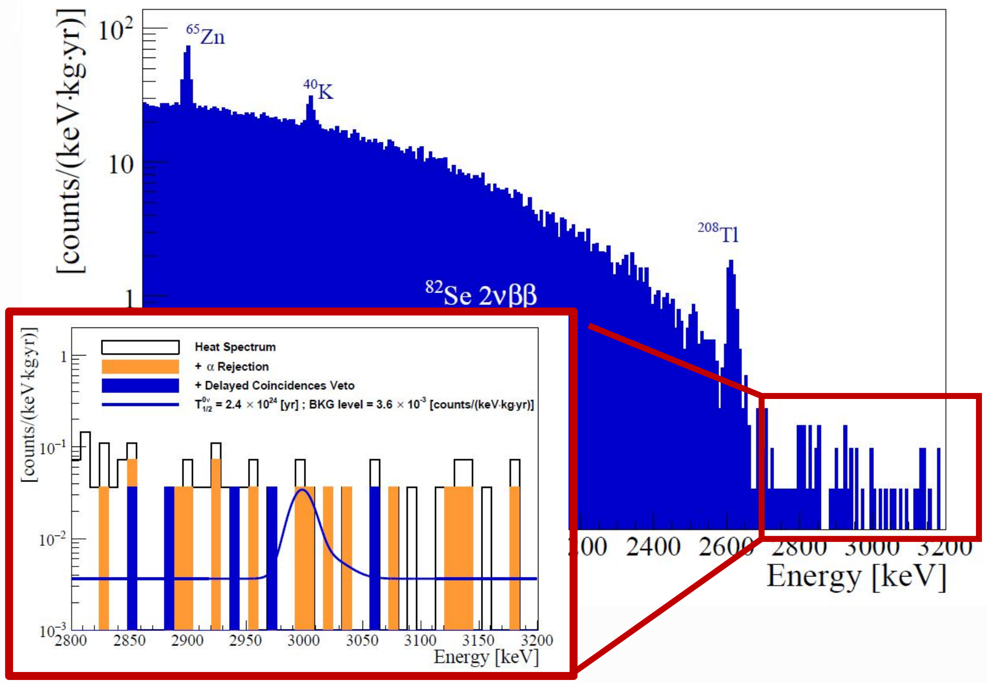


CUPID-0 results

- Demonstration of dual-readout technique
- An unprecedented BKG level for a bolometric experiment was reached:
  3.6 × 10^{-3} counts/keV/kg/yr
- The best limit on ^{82}Se 0v2β half-life (with exposure 1.83 kg×yr of ^{82}Se)
  $$T_{1/2}^{0v2\beta} = 2.4 \times 10^{24} y \text{ @ } 90\ \%\ \text{C. L.}$$

Phys. Rev. Lett. 120, 232502 (2018)





From LUMINEU R&D to CUPID-Mo

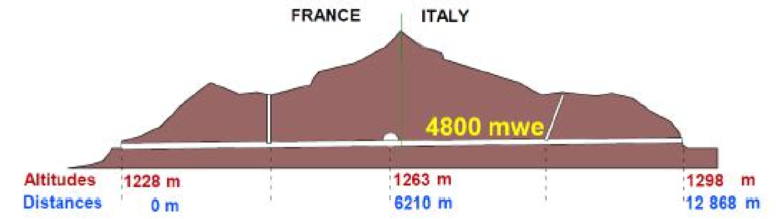
- **Protocol of $Li_2{}^{100}MoO_4$ production was developed:**
  - **Mo purification / crystallization protocols**
  - Successful program to **control ^{40}K content** (< 5 mBq/kg)
  - Efficient use of existing **10 kg of ^{100}Mo**

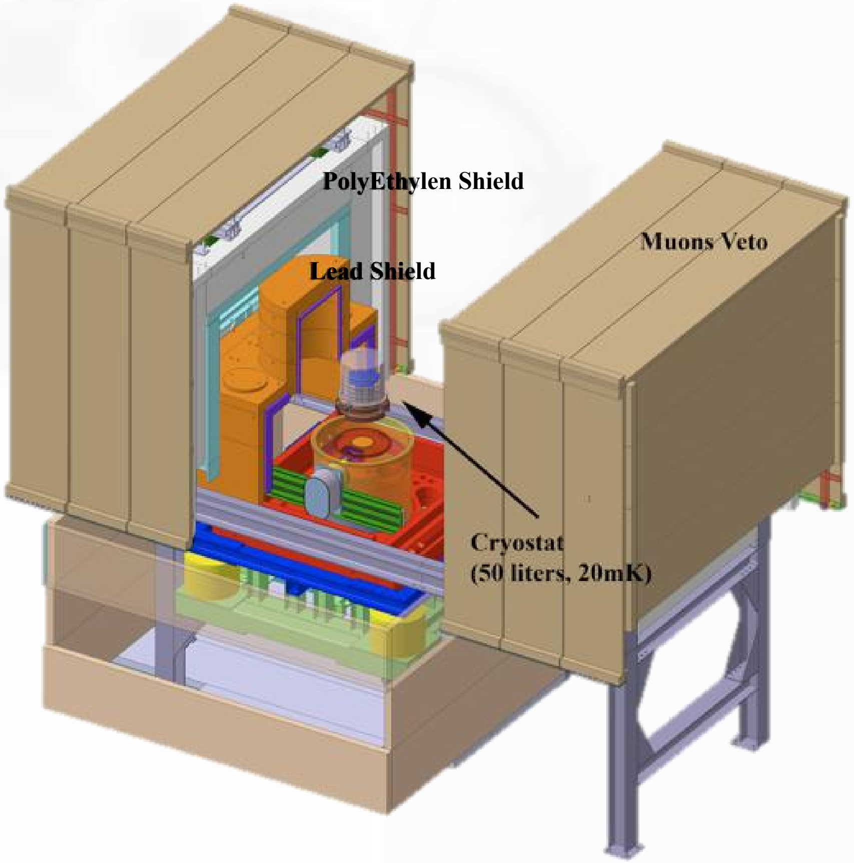
- **Batch of 20 $Li_2{}^{100}MoO_4$ crystals of 0.2 kg each was produced:**
  - high optical quality
  - high crystal yield **(~ 80-85%)**
  - low irrecoverable losses of ^{100}Mo **(~3%)**

LSM underground laboratory

- **Laboratoire Souterrain de Modane (LSM):**
  - Frejus tunnel
- 1.7 km rock overburden (~4.8 km w.e.)
  - cosmic μ reduction= 10^{-8}(1/m^{2}h)
  - Deradonized air flow (~30 mBq/m^3)

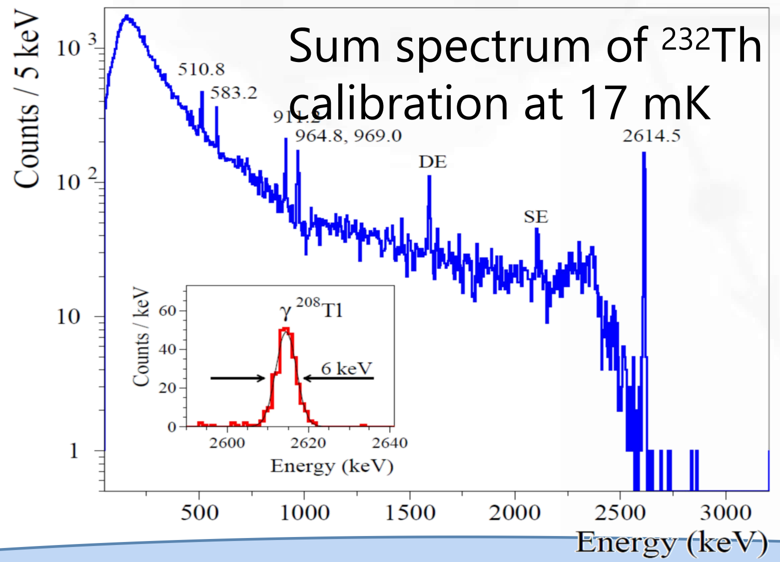
- **EDELWEISS set-up:**
- Clean room
- Copper cryostat
- Low radioactivity lead (min. 20 cm)
- Polyethylene (min. 50 cm)
- Monitoring of μ / n / Ra
- Muon veto

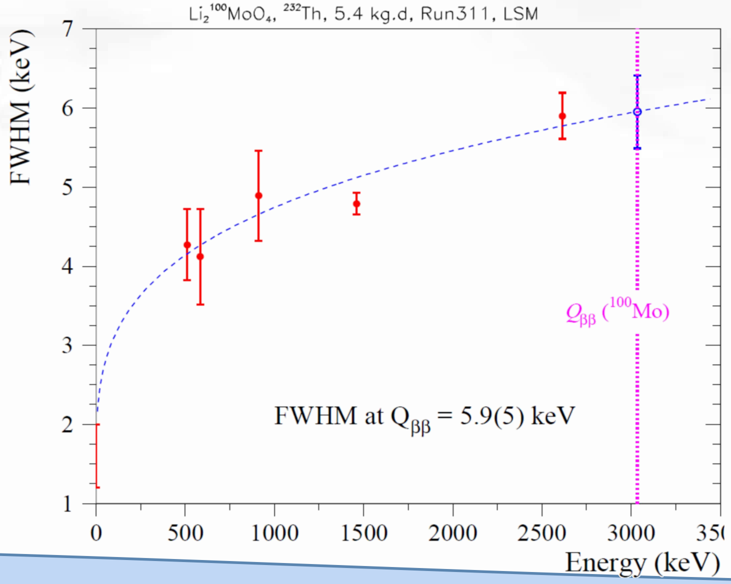


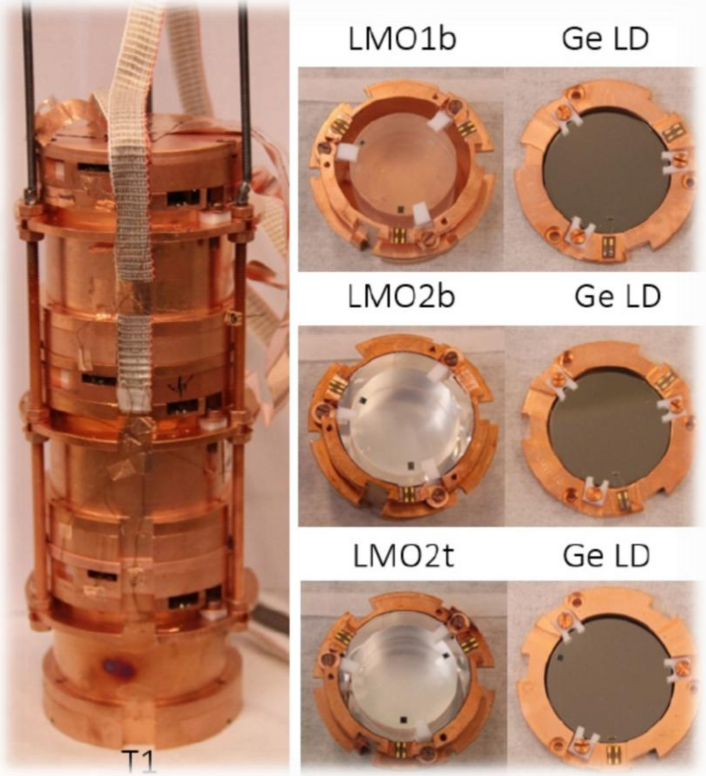


$Li_2{}^{100}MoO_4$ scintillating bolometers performance

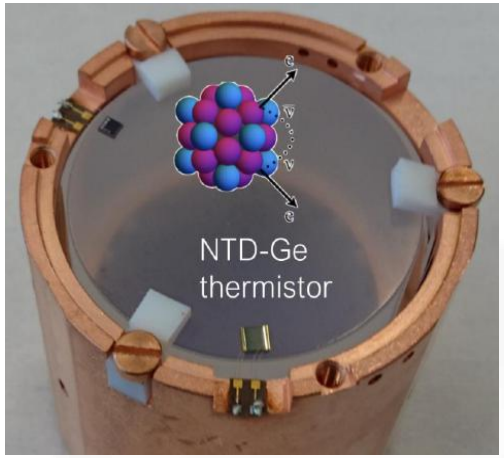
- Multiple tests with natural and enriched crystals were performed in 2014-2017 with excellent results:
- uniform performance, good reproducibility
- high energy resolution: **4-6 keV FWHM** in ROI **(~0.2%)**
- rejection of α's at the level of **>9σ**
- high radiopurity: **^{232}Th, ^{238}U <6 μBq/kg, ^{40}K< 1.3 mBq/kg**

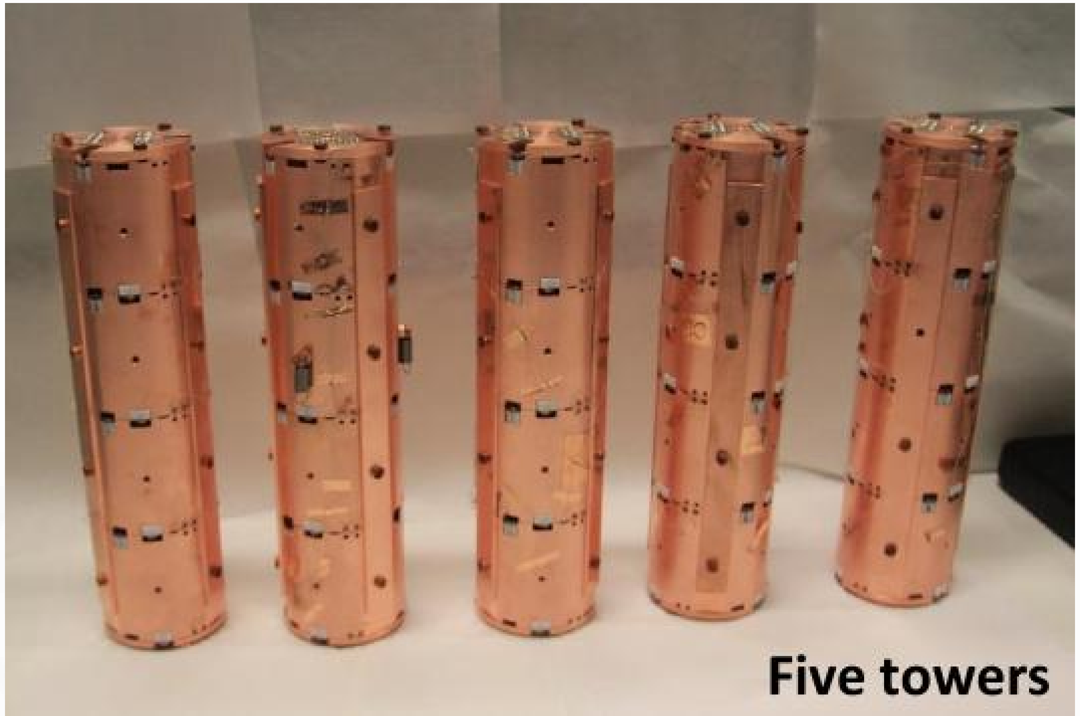




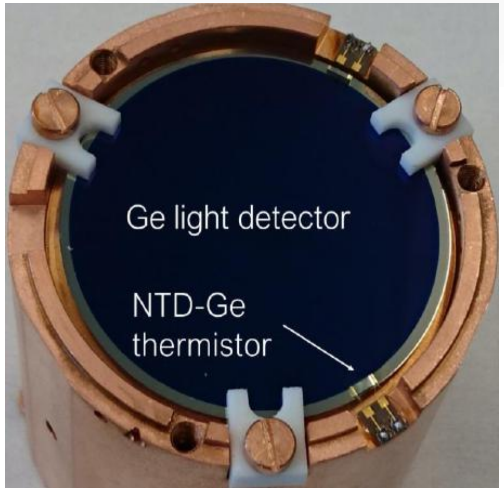


CUPID-Mo detectors



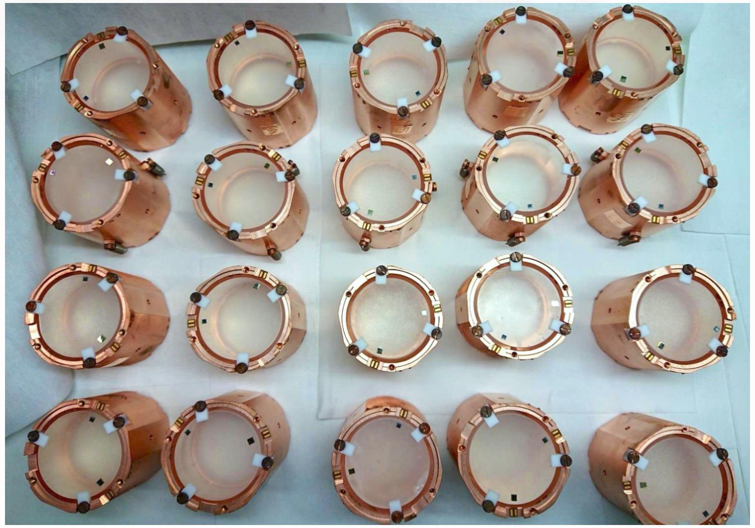


× 20

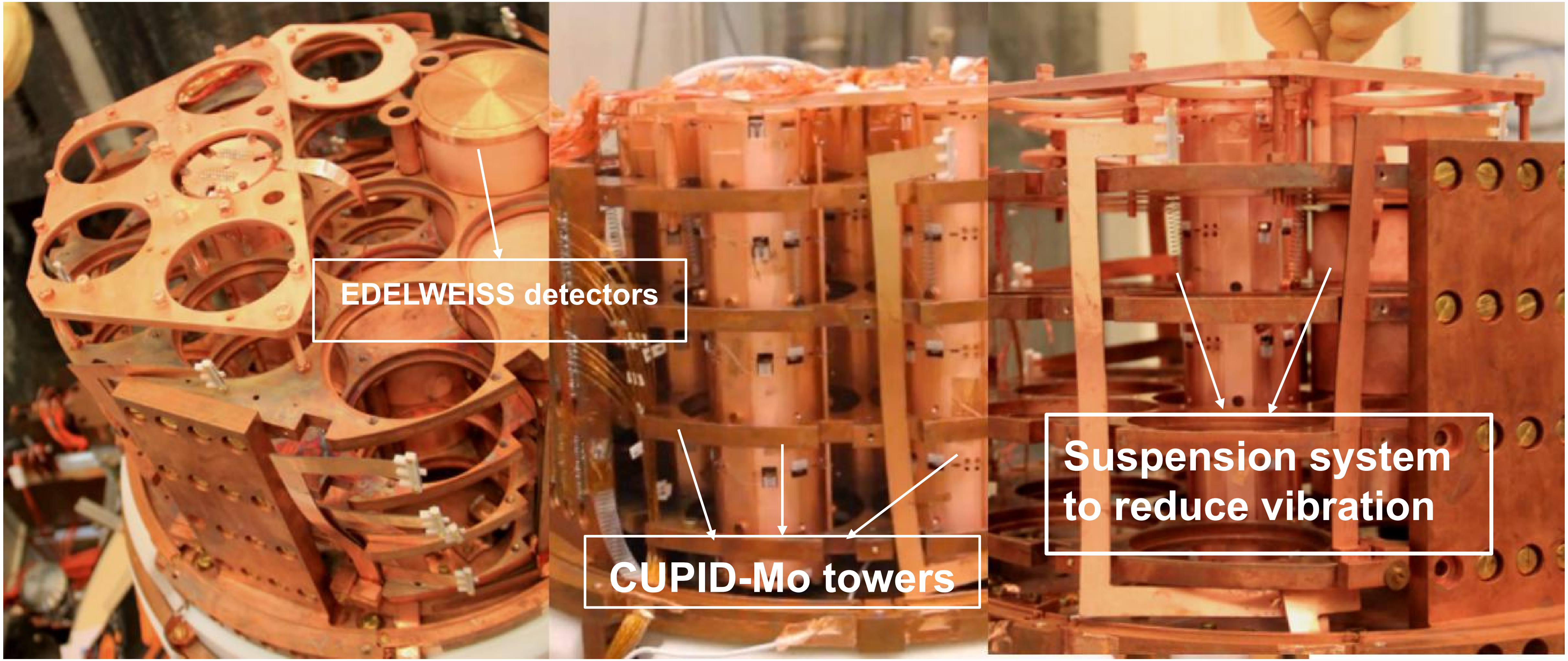


20 x $Li_2{}^{100}MoO_4$ (D44*45 mm, ~0.21 kg)

- Enrichment 96.6 ±0.2 %
- 4.158 kg $Li_2{}^{100}MoO_4$
- 2.264 kg ^{100}Mo

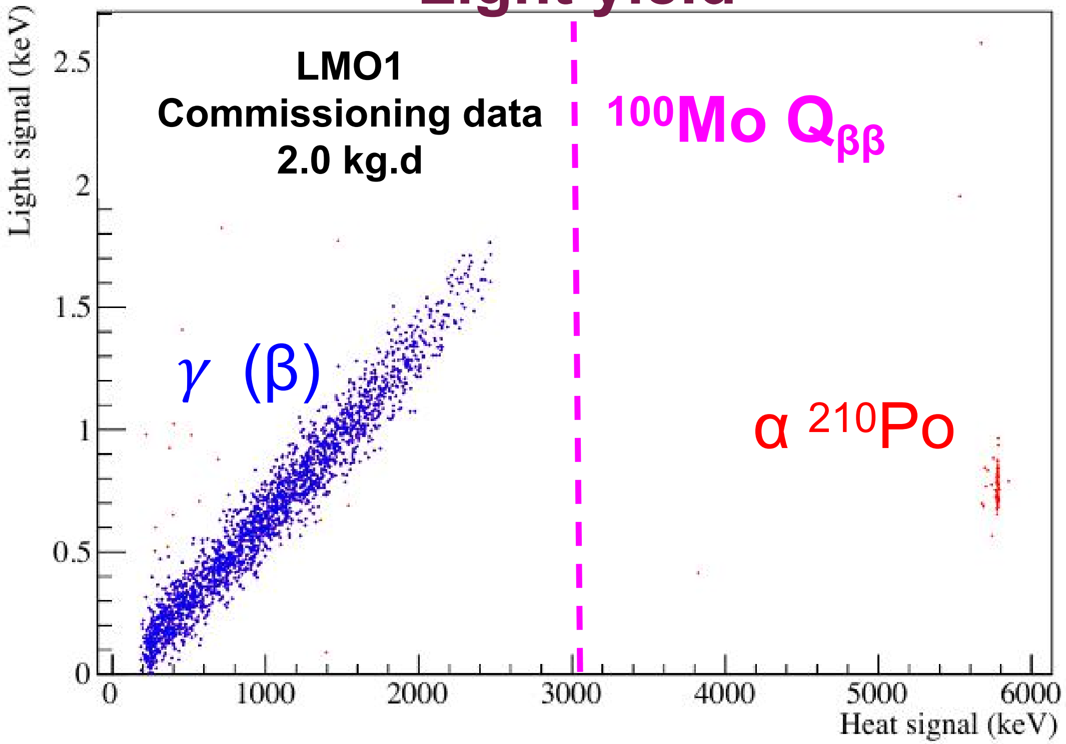


The CUPID-Mo experiment at Modane

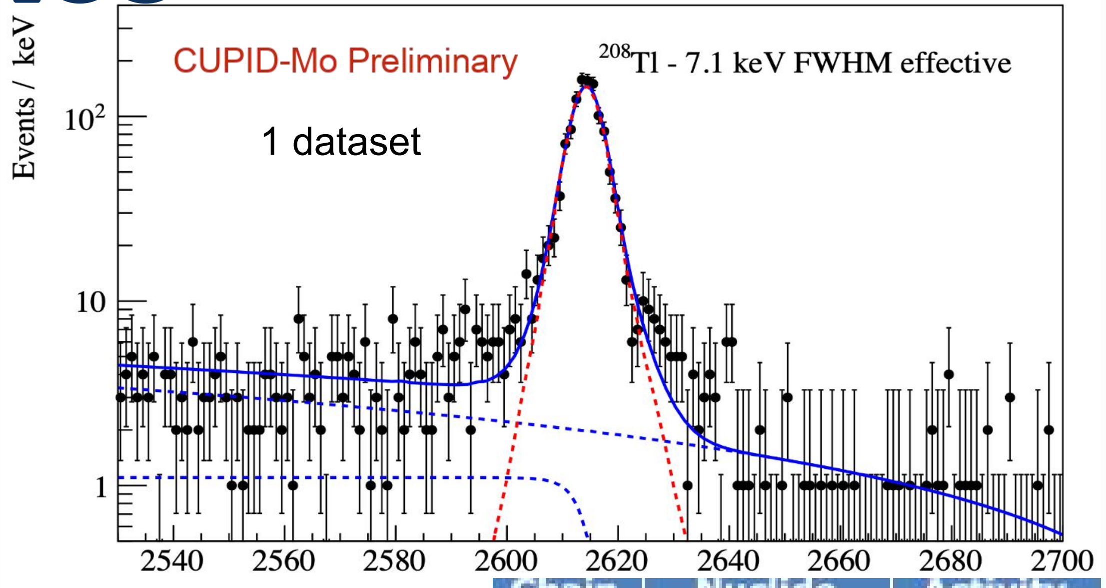


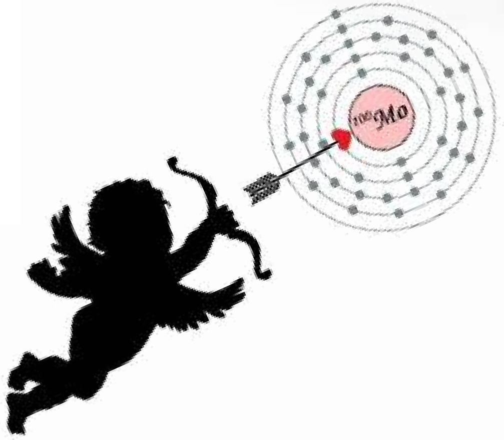
CUPID-Mo performance

Light yield



- **Typical γ (β) LY: 0.6-0.7 keV/MeV**
- **Quenching factor of α: 20%**
- **> 99.9 % of γ (β)/α separation**

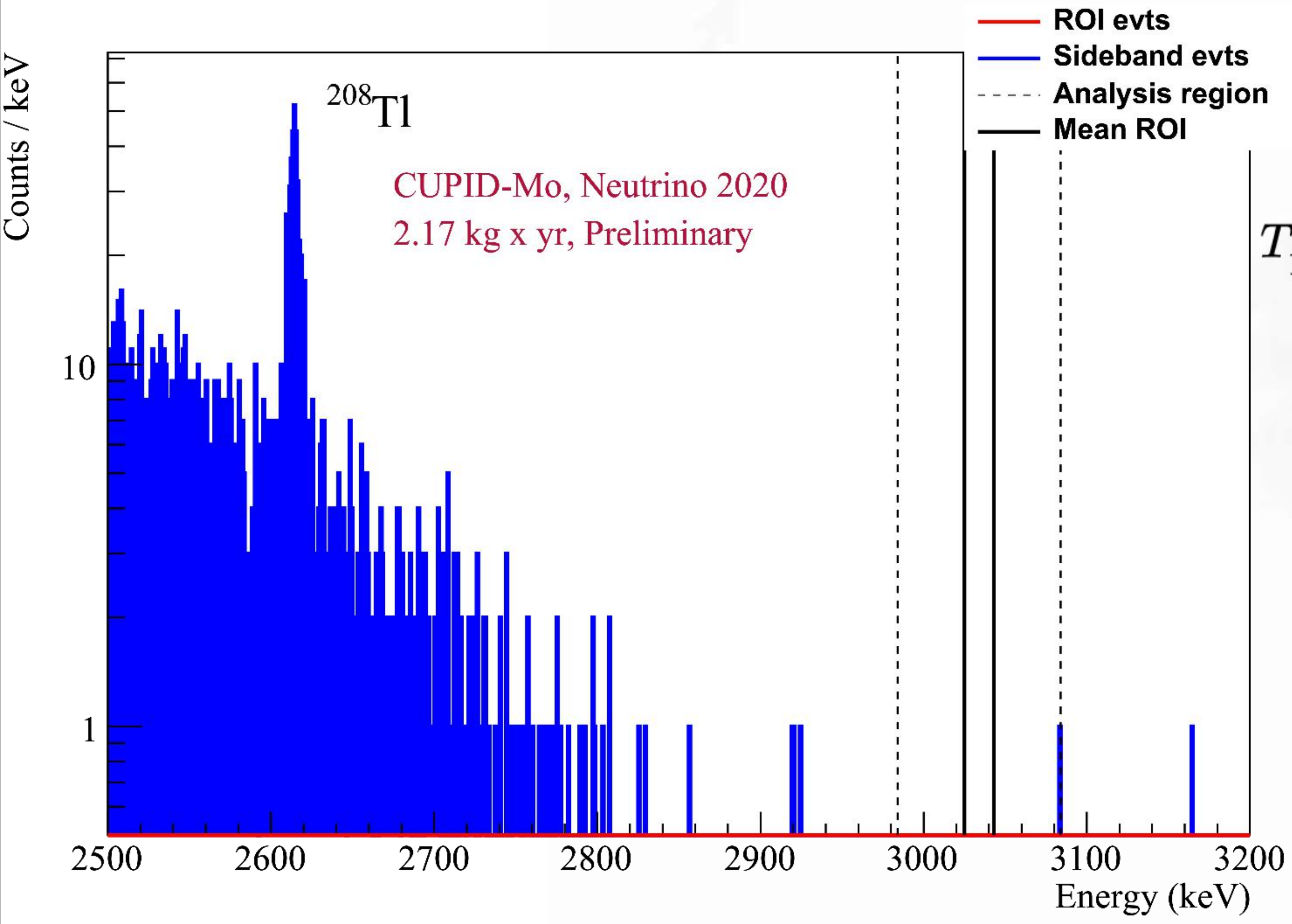




Radiopurity

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Th	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	95(6)
	^{190}Pt	0.19(8)

The new $0\nu\beta\beta$ decay CUPID-Mo limit



New world leading limit

$$T^{0\nu}_{1/2} > 1.4 \times 10^{24} yr, \; 90\% \; C.I. \; (stat.+syst.)$$

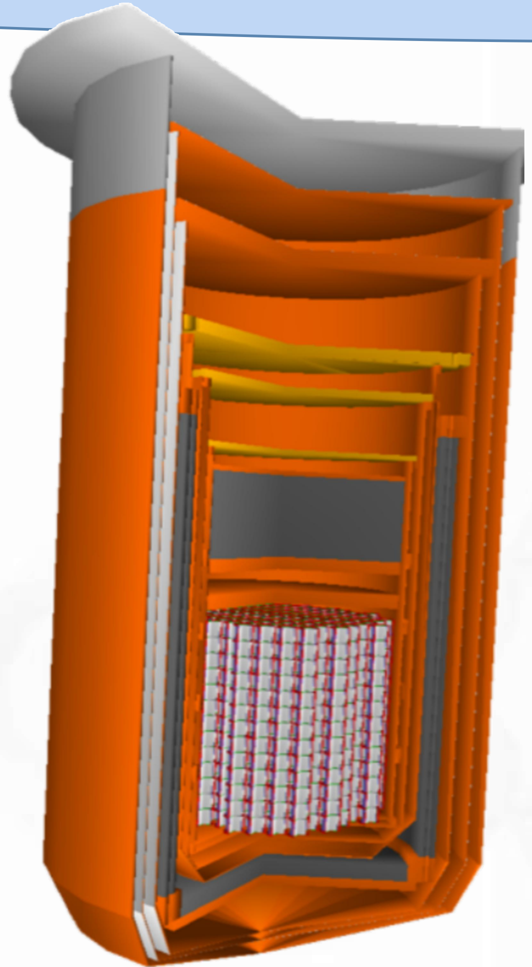
Effective Majorana mass

$$m_{\beta\beta} < (0.31 - 0.54) \; eV$$

considering g_A= 1.27 and dependent on the Nuclear Matrix Element in the light Majorana neutrino exchange interpretation

CUPID: baseline

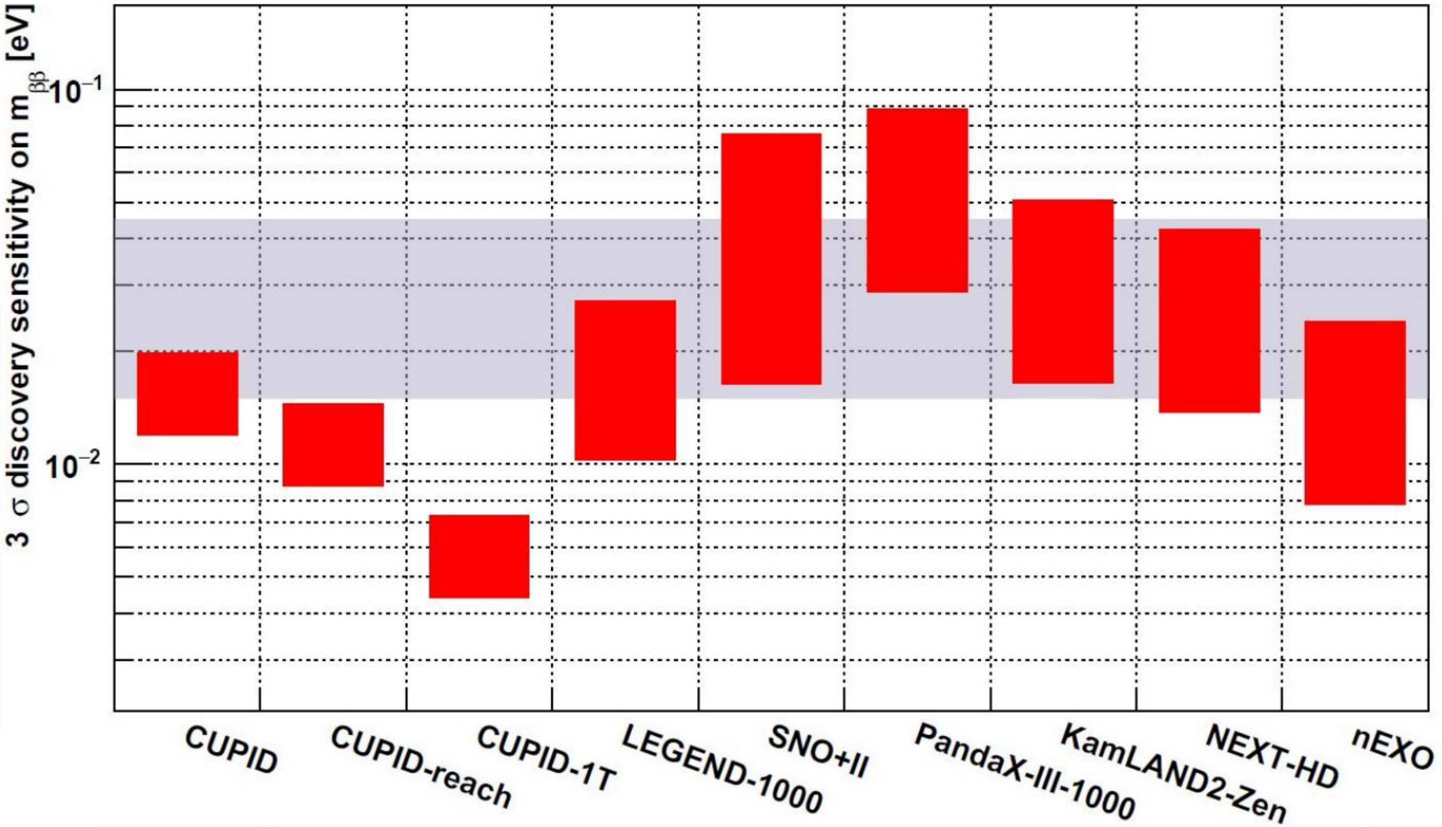
- **$Li_2{}^{100}MoO_4$ scintillating crystals**
- Alpha rejection using light signal
- Enrichment > 95%
- Cubic crystals 45 x 45 x 45 mm3
- 1500 crystals ~250 kg 100Mo
- FWHM ~ 5 keV at $Q_{\beta\beta}$ (3034 keV)
- Comissioning and datataking in ~7 years from now



Different tower structures are being tested

Background goal: 10^{-4} cts/(keV kg y)
Discovery sensitivity:
$T^{1/2}(^{100}Mo) > 10^{27}$ y, $m_{\beta\beta} < 20$ meV

CUPID: sensitivity



- CUPID: Exactly what we could start building today:**10^{-4}** cts/(keV kg y)
- CUPID-reach: improvements at reach before construction: **2×10^{-5}** cts/(keV kg y)
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **5×10^{-6}** cts/(keV kg y)

β surface radioactivity

^{238}U chain → ^{214}Bi β Q value: 3.3 MeV
(^{210}Tl Q value: 5.5 MeV- 0.02% ^{214}Bi)

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow[164\ \mu s]{\alpha} {}^{210}Pb$

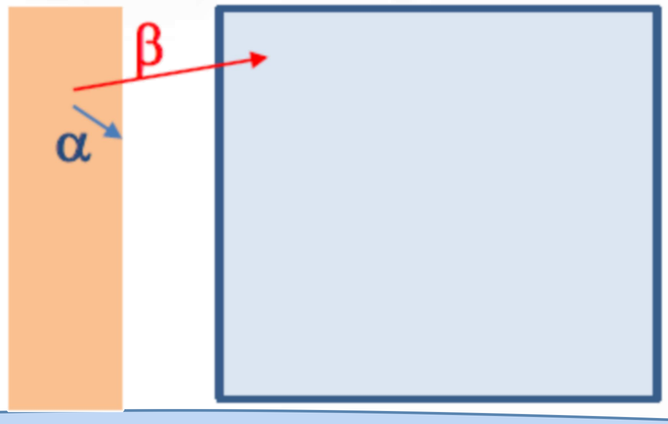
Harmless in the crystal bulk
Mixed α/β event

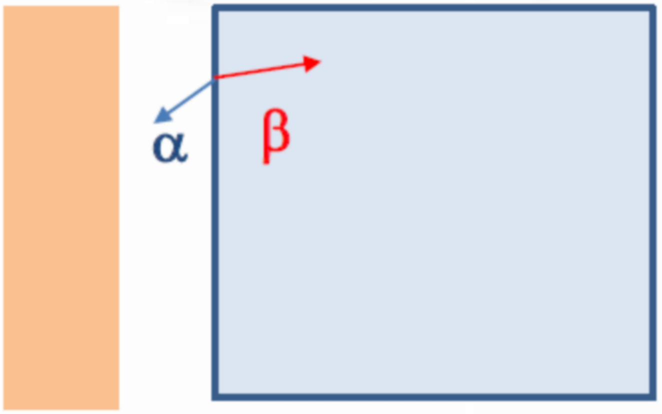
^{232}Th chain → ^{208}Tl β Q value: 5.0 MeV

$^{212}Bi \xrightarrow{\alpha} {}^{208}Tl \xrightarrow[3.053\ min]{\beta} {}^{208}Pb$

Under control in the crystal bulk
Delayed coincidence

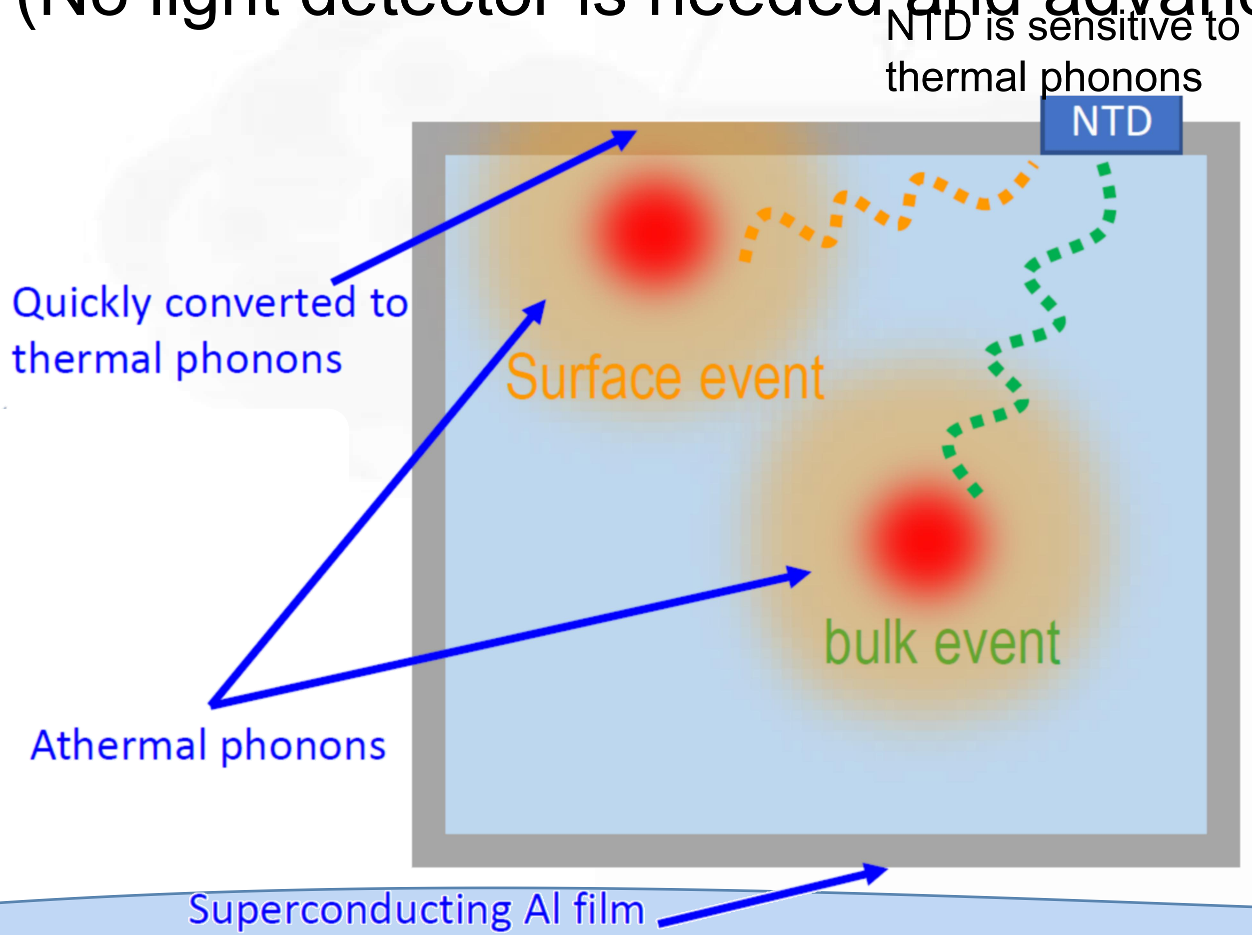
These processes become challenging at the surface → it may happen that α escape detection and β is (partially) absorbed

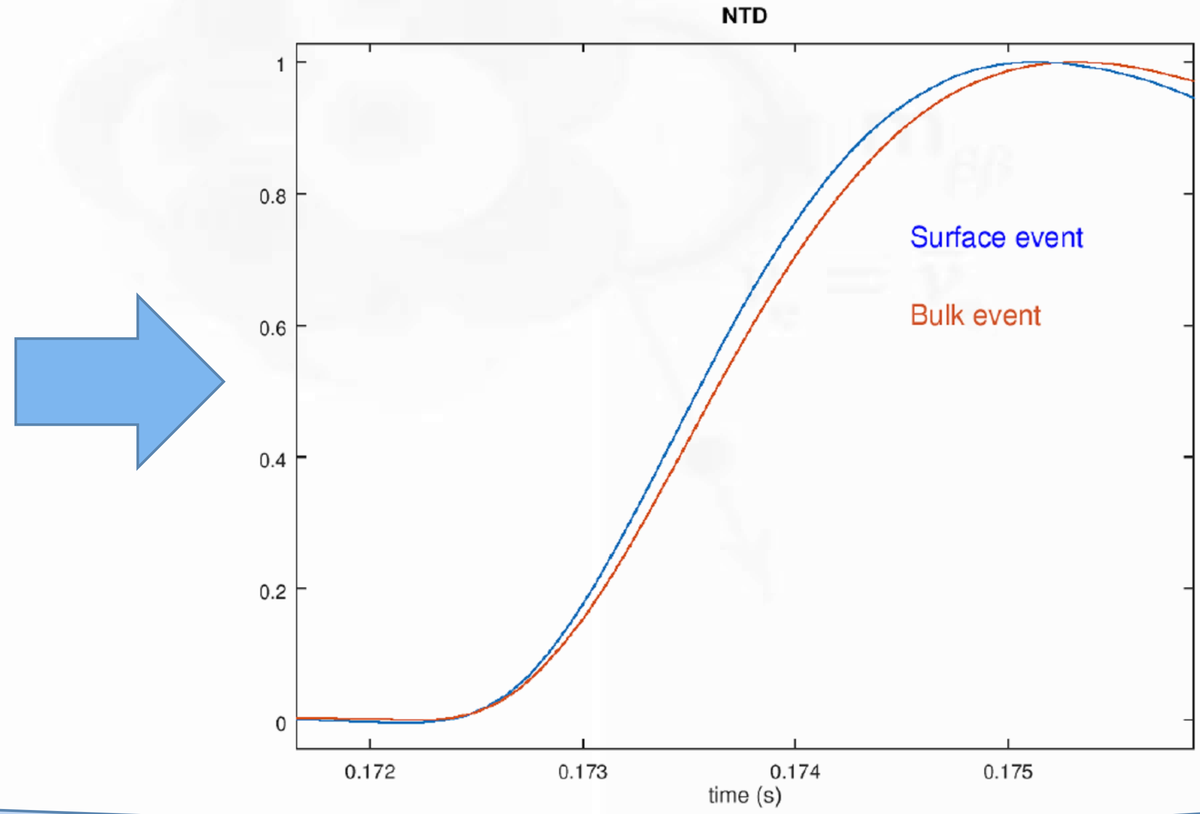




CROSS technology: surface sensitivity

Bolometers with superconducting films to identify near-surface events
(No light detector is needed and advanced particle ID)





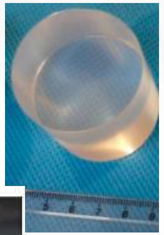
CROSS isotopes and bolometers

^{100}Mo - first choise: **Q = 3034 keV > 2615 keV** **A.I.: 9.7%**

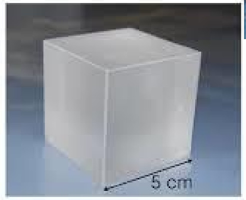
^{130}Te - kept as an option: **Q = 2527 keV < 2615 keV** **A.I.: 34%**

Crystals:

Li_2MoO_4 - basic choise for CUPID



TeO_2 - CUORE compound



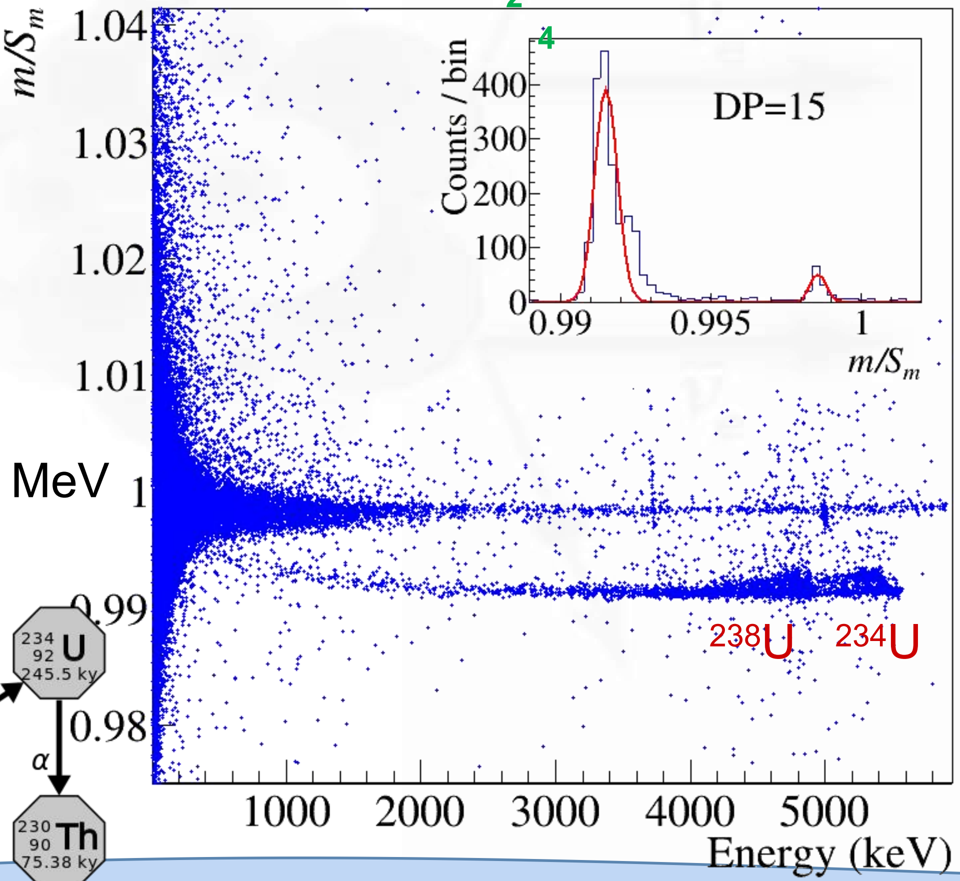
Excellent bolometric properties
High radiopurity
Extensively tested

10.1007/JHEP01(2020)018

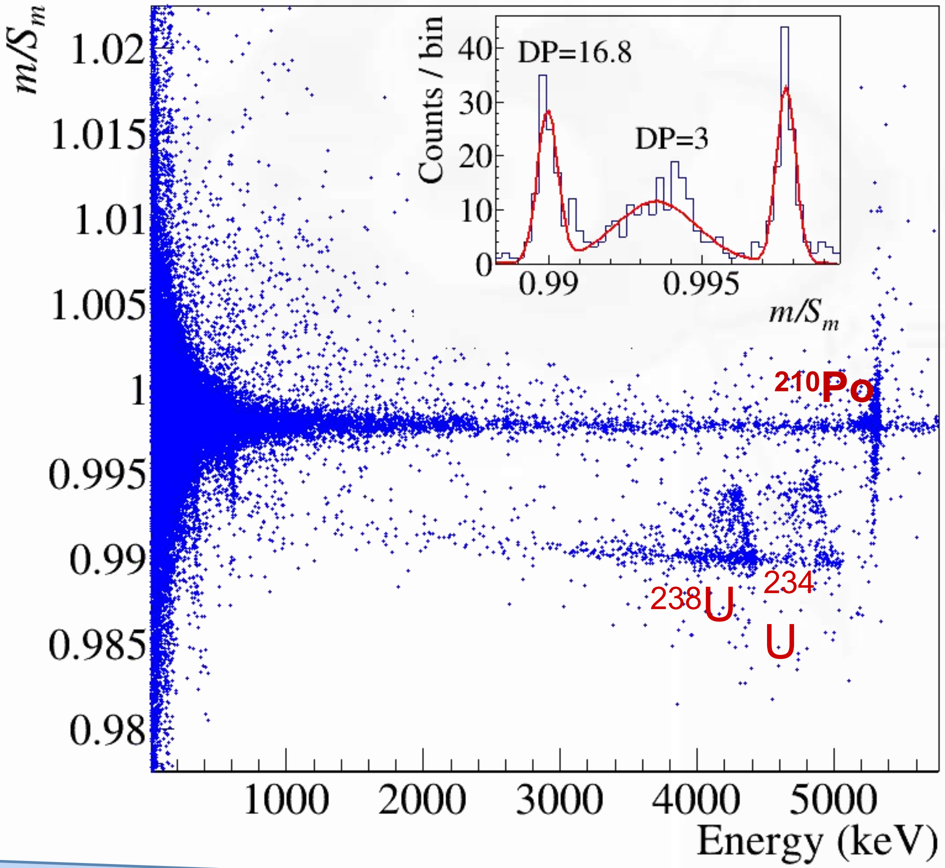
CROSS prototypes: 10 um Al coating

- Prototypes are tested in aboveground tests (IJCLab) with coating on one face, directed to U source

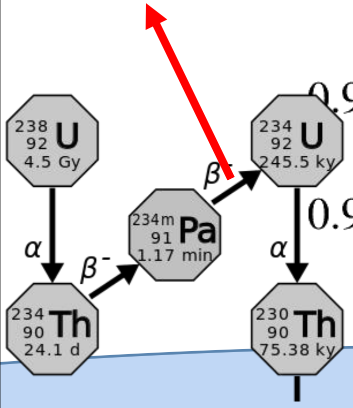
Li_2MoO_4



TeO_2



Endline 2.2 MeV

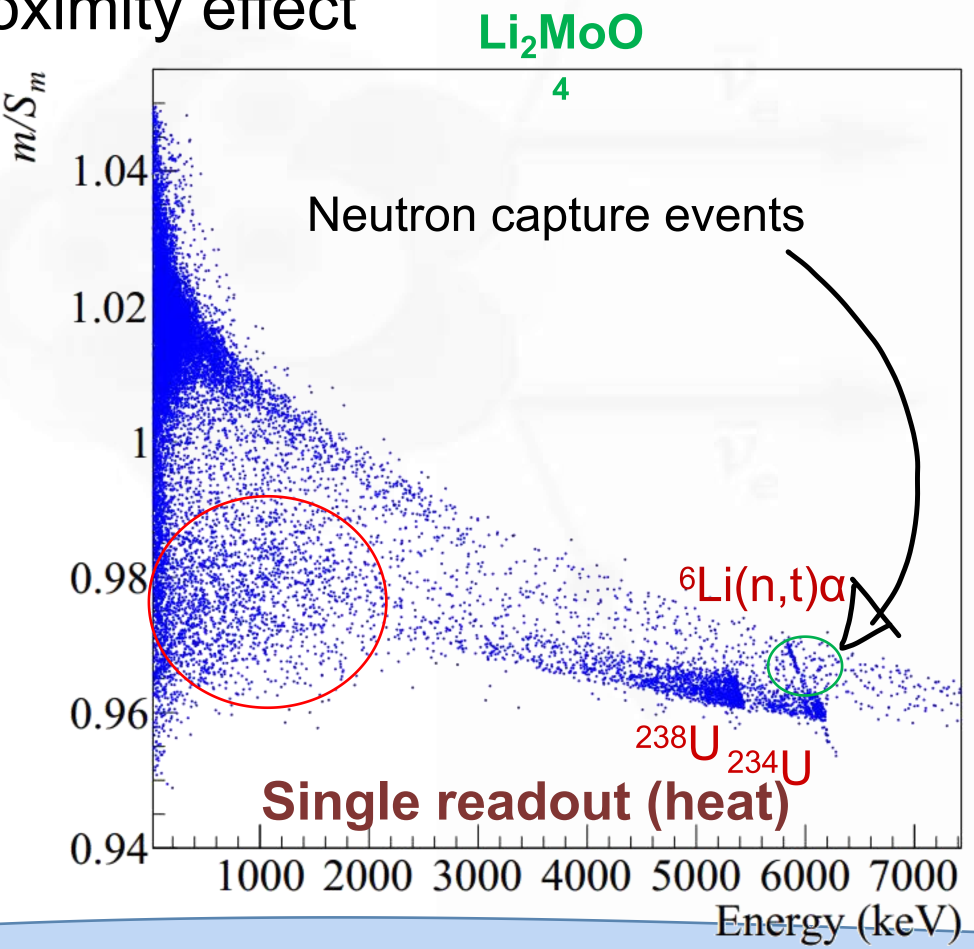


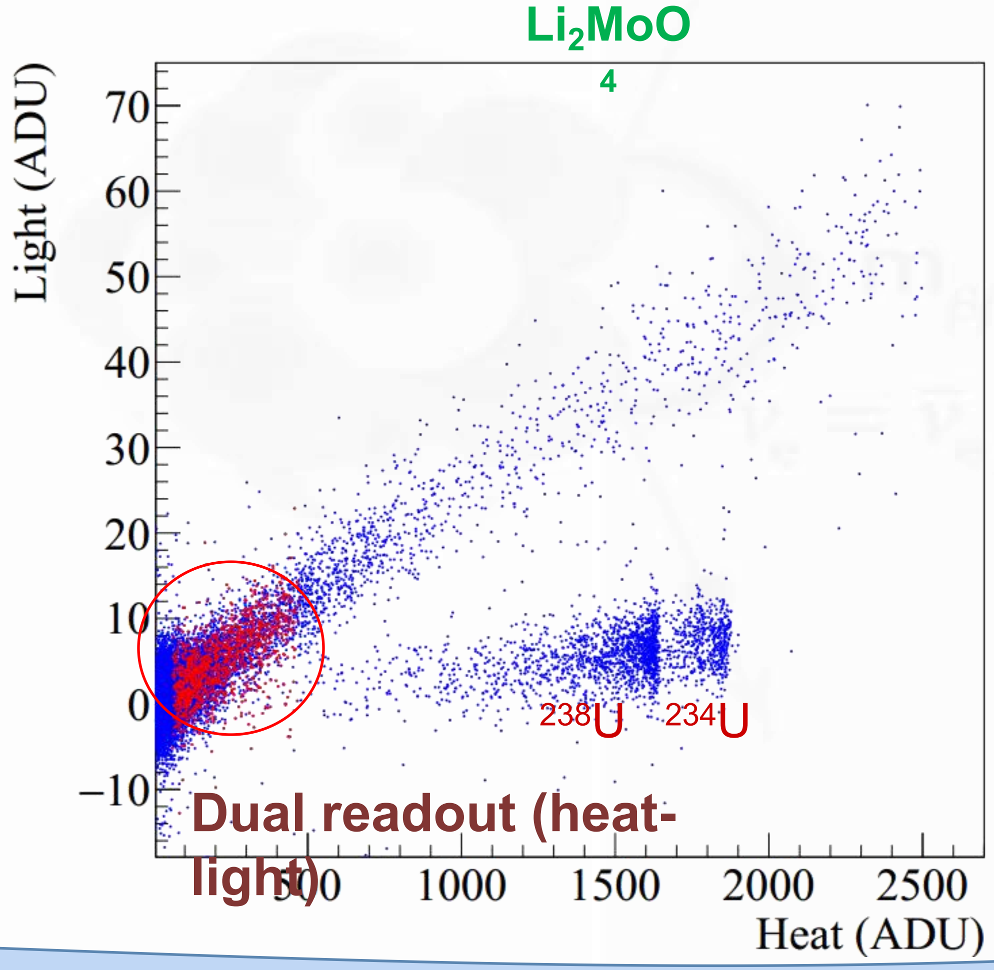
Discrimination power:

$$DP=\frac{|\mu_{\beta/\alpha}-\mu_{\alpha}|}{\sqrt{\sigma^2_{\beta/\gamma}+\sigma^2_{\alpha}}}$$

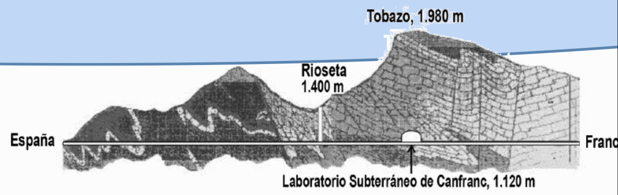
CROSS prototypes: Al-Pd coating

- Normal metal (Pd) is a better thermalizer, Al reduces the heat capacity due to the proximity effect



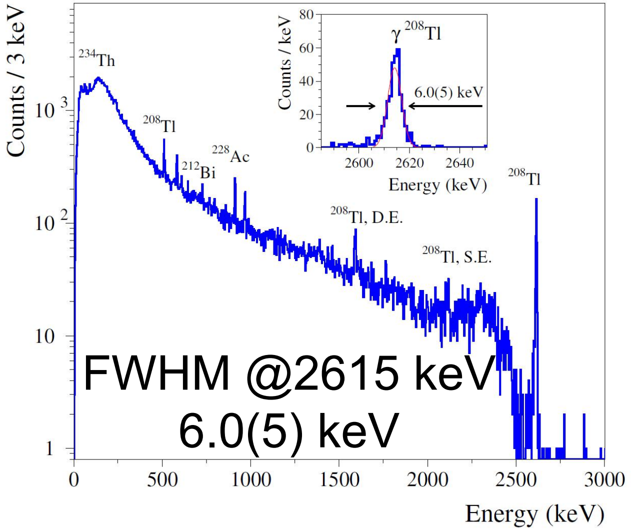


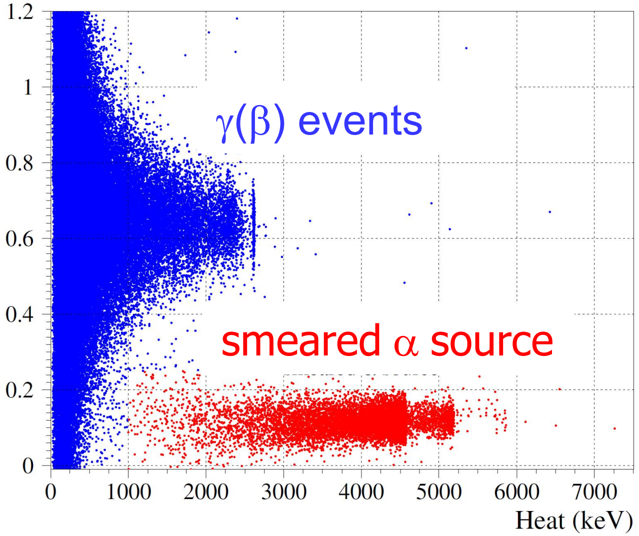
CROSS underground facility

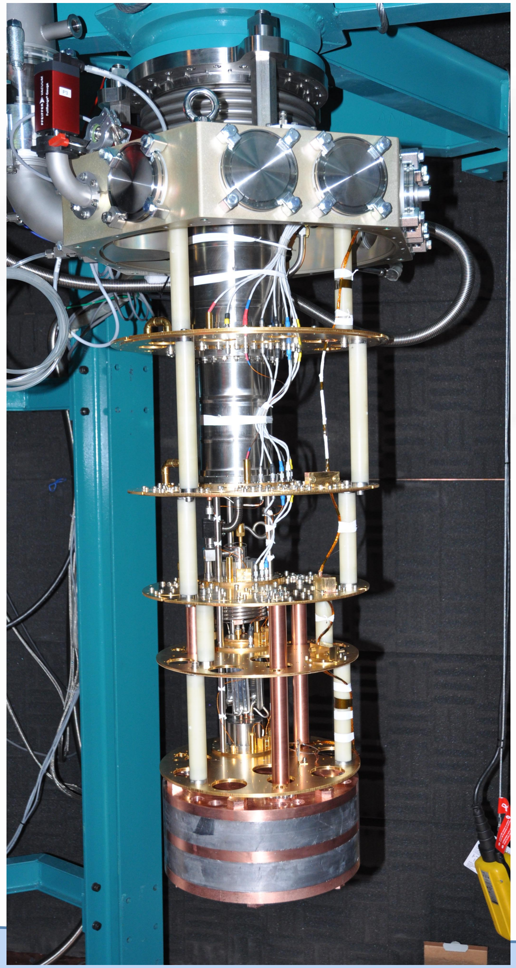


LSC
Laboratorio Subterráneo Canfranc

- Cryostat installed and commissionned in April 2019
- This facility will be used also for the final definition of the CUPID structure
- 99% duty cycle, high stability, excellent performance of bolometers





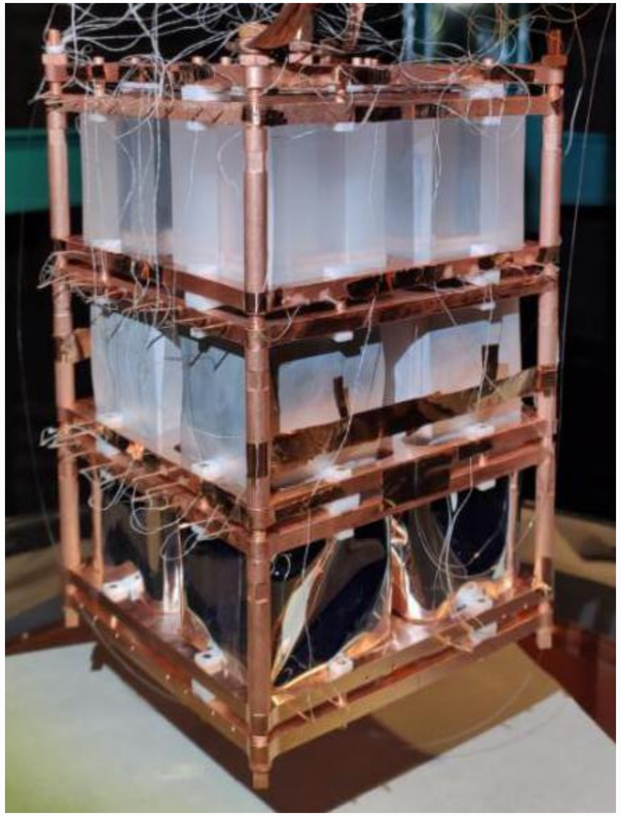


CROSS / CUPID ENTANGLEMENT

The Canfranc CROSS facility is / will be used for a series of tests aiming at defining the final structure of the CUPID detector.

- Validation of the cubic shape of the Li_2MoO_4 crystals
- Optimization of the NTD sensors
- Validation of innovant calibration methods for light
- Study of Neganov-Trofimov-Luke light detectors
- Light collection studies
- Validation of the electronics and custom DAQ boards for CUPID
- Set up of a new protocol for enrichment / purification / crystallization
- Decision on the light detectors configuration
- Design and development of detectors mechanical structure
- Validation of the selected options with a multi-detector tower

Done - Ongoing - Future



COMPOSITION OF THE CROSS DEMONSTRATOR

Currently available $Li_2{}^{100}MoO_4$ crystals:

- **32** cubic crystals [45x45x45 mm – 280 g] grown from NEMO-3 enriched ^{100}Mo
- **20** cylindrical crystals [∅44x45 mm – 210 g] from CUPID-Mo grown from NEMO-3 enriched ^{100}Mo

Under procurement Li_2MoO_4 crystals:

- **16** cubic crystals [45x45x45 mm – 280 g] grown from freshly-enriched Mo [test new enrichment/purification chain]

Under procurement TeO_2 crystals:

- **4 through 8** crystals [50x50x50 mm – 750 g] grown from existing enriched Te [test new purification/crystallization c

The final configuration of the demonstrator is still under discussion, depending on the mechanical structure to hold cry

Minimum configuration: **32 Li_2MoO_4 crystals – 4 TeO_2 crystals**

Maximum configuration: **68 Li_2MoO_4 crystals – 8 TeO_2 crystals**

Summary

- **Bolometric technology** is a promising approach for double beta decay searches with **high energy resolution**;

- **CUPID-Mo** set a new world **leading limit** on the $0\nu2\beta$ decay of ^{100}Mo

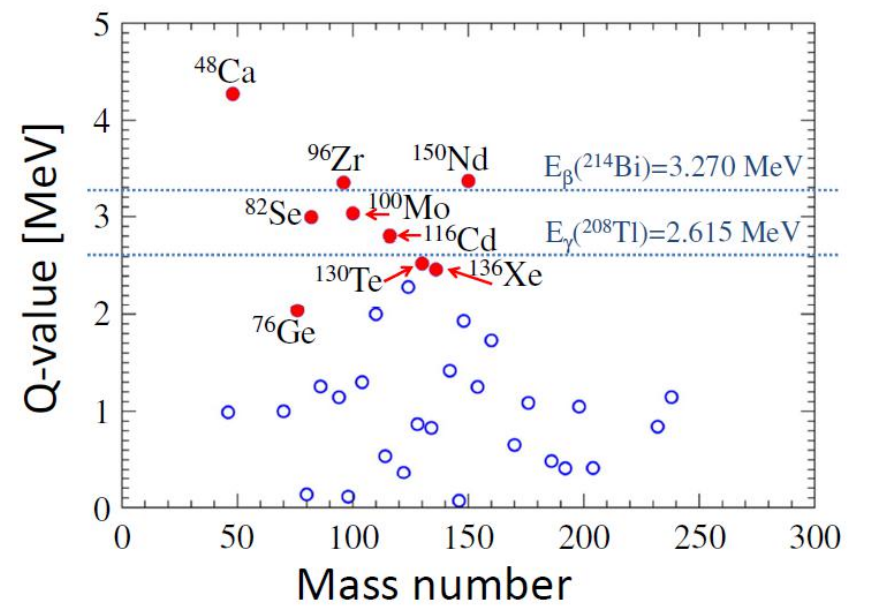
- The **LUMINEU/CUPID-Mo** technology is the baseline for the future ton-scale experiment **CUPID** at LNGS, aiming to couver completely the inverted hierarchy region, discovery sensitivity: **$T^{1/2}(^{100}Mo) > 10^{27}$ y, $m_{\beta\beta} < 20$ meV**

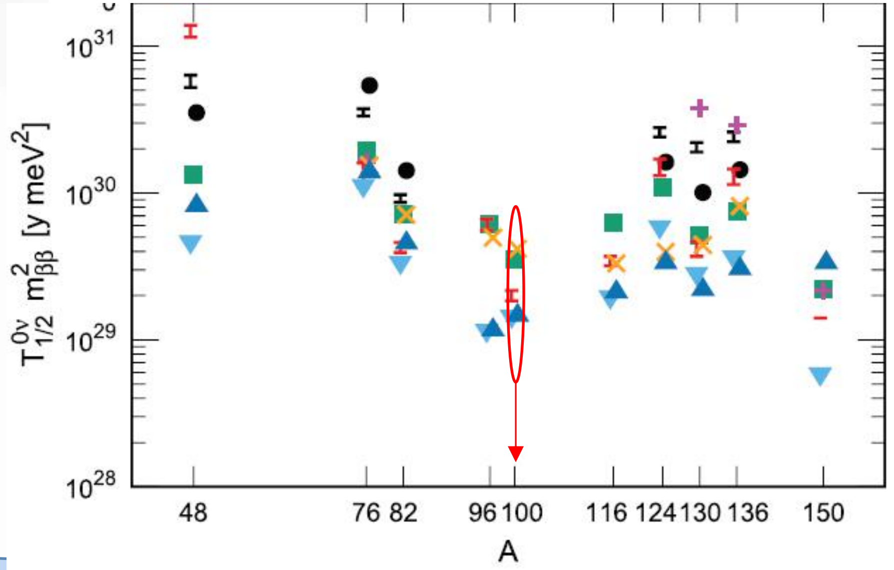
- **CROSS experiment** proposes effiecient discrimination of surface α and β events, demonstrator experiment should prove the technology robustness, allowing to reach **10^{-5} cts/(keV kg y)** bkg level for future ton-scale experiments

Backups

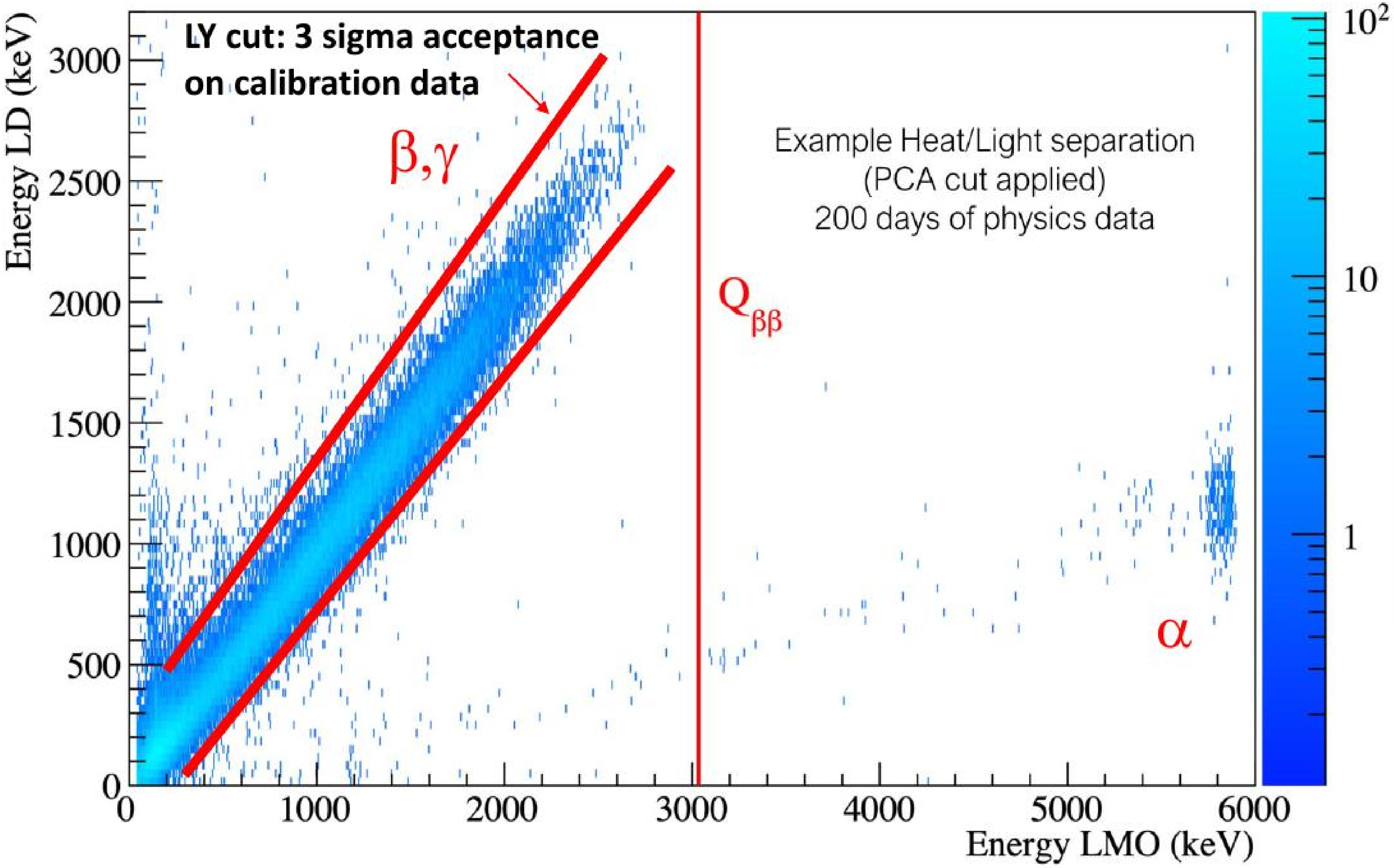
Isotope selection: why ^{100}Mo?

- High transition energy: $Q_{\beta\beta}$ **= 3034 keV**
- Natural abundance = 9.7%
- **Large-scale enrichment** is possible
- **Favorable theoretical predictions**
- High detection efficiency, energy resolution and powerful particle discrimination (**cryogenic scintillating bolometers**)

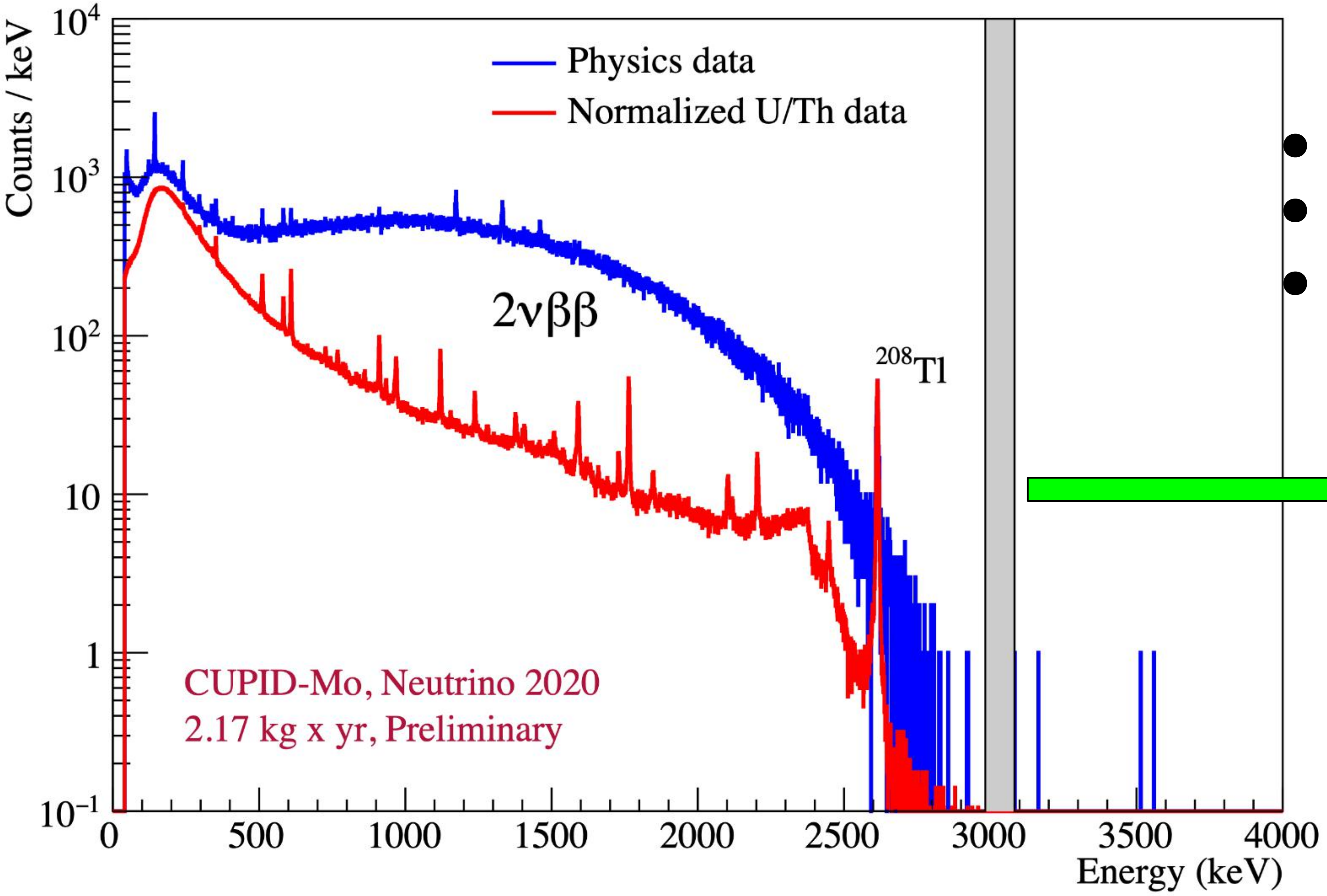


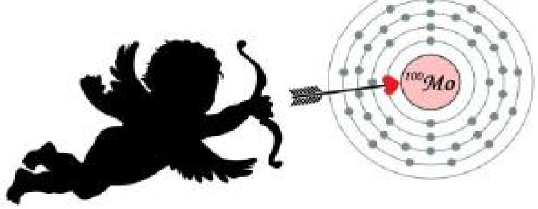


Light yield cut



CUPID-Mo blinded data





- 200 days of physics data
- 19/20 detectors
- ~7 keV FWHM @ 2615 keV (calibration)

Blinded region = 100 keV centred around $Q_{\beta\beta}$

Background goals: CUPID and beyond

Pure bolometer: CUORE
Background dominated by surface α's

Reject α's

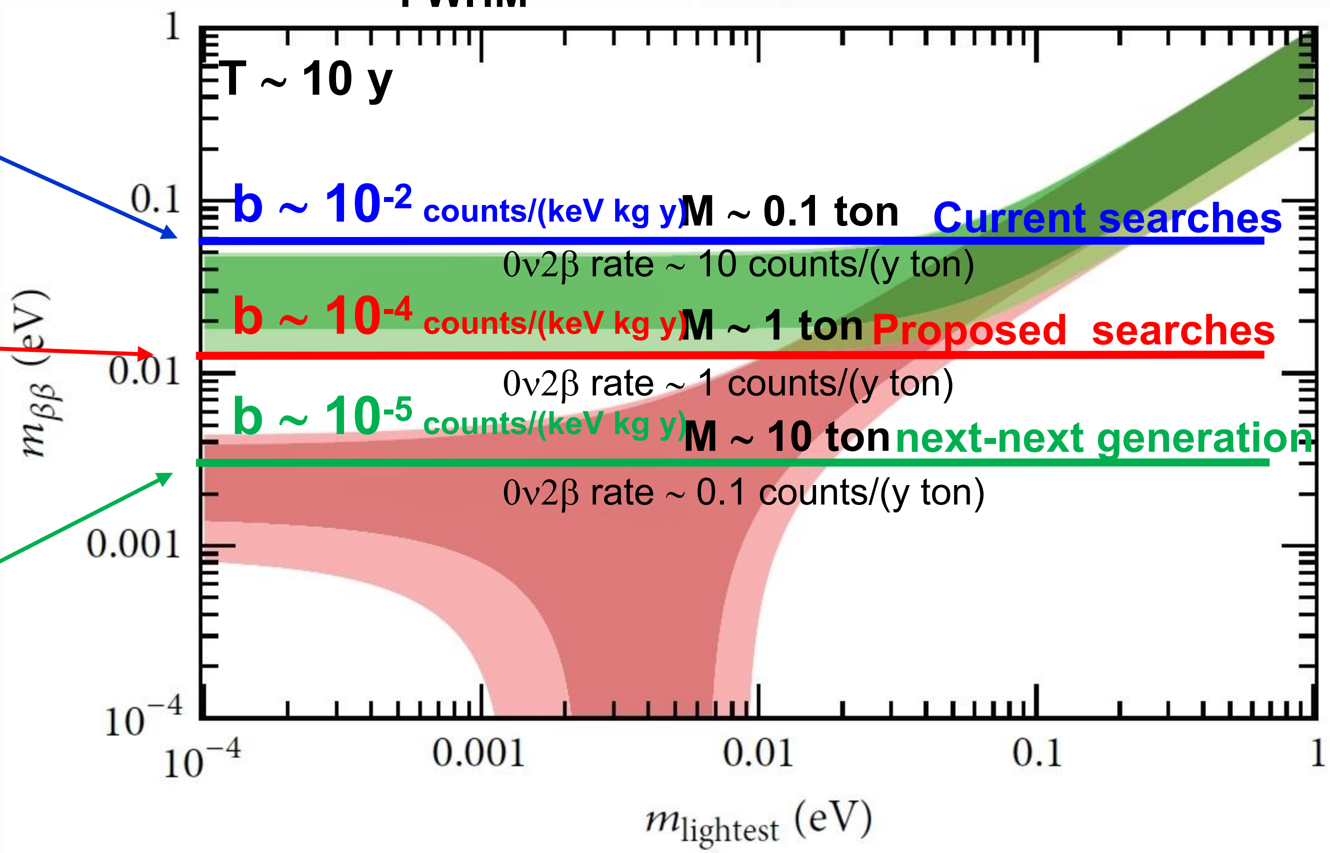
Scintillating bolometer: CUPID
Important contribution from surface β's

Reject surface α's & β's

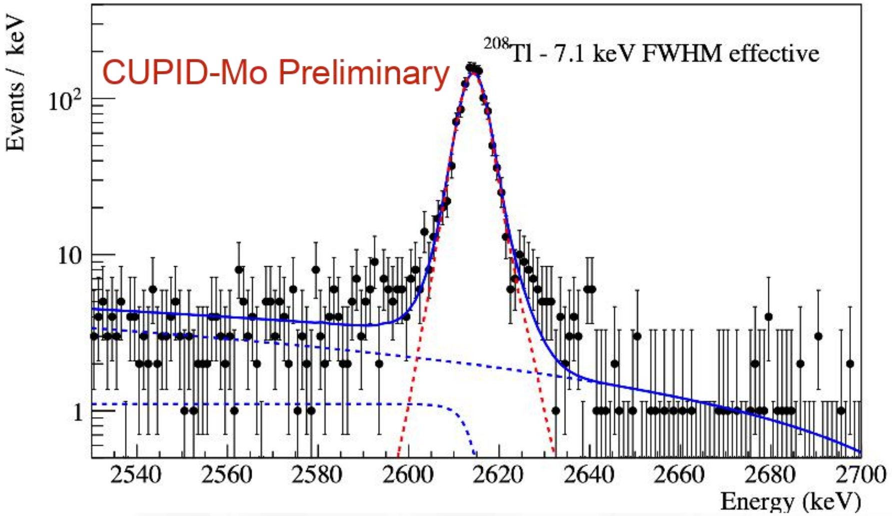
Surface sensitive bolometer: CUPID-like experiment with CROSS technology

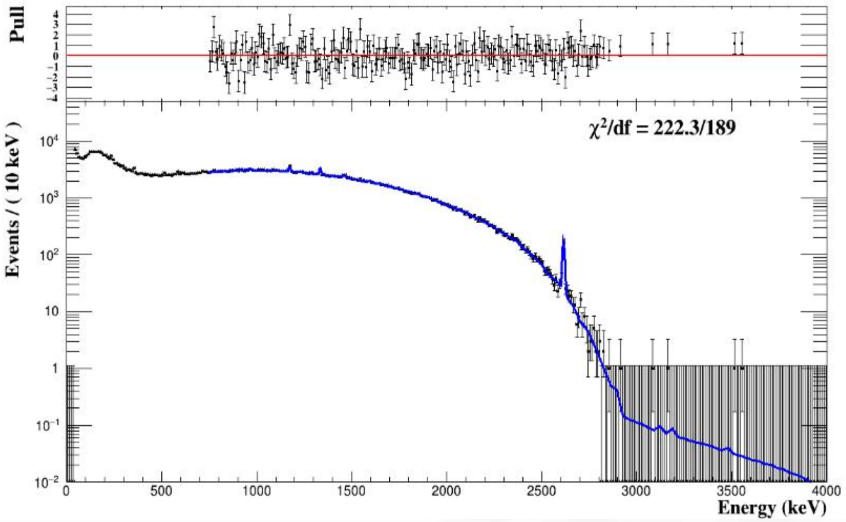
Bkg rate in ROI ~ b × M × ΔE_{FWHM}

ΔE_{FWHM} **~ 5 keV** for bolometers

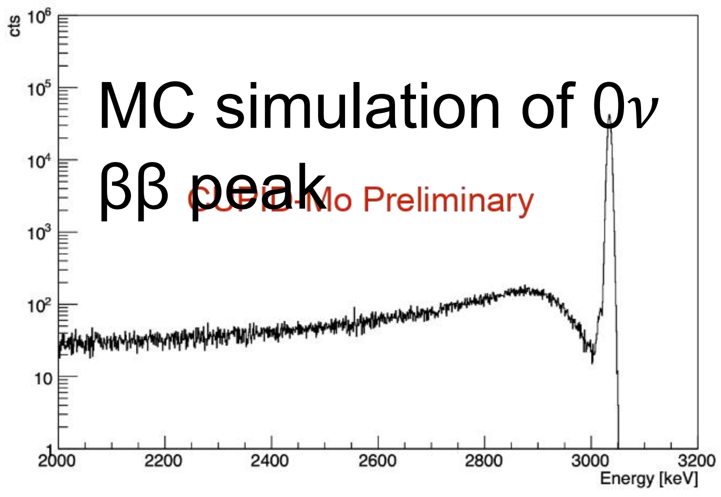


How did we define our ROI?



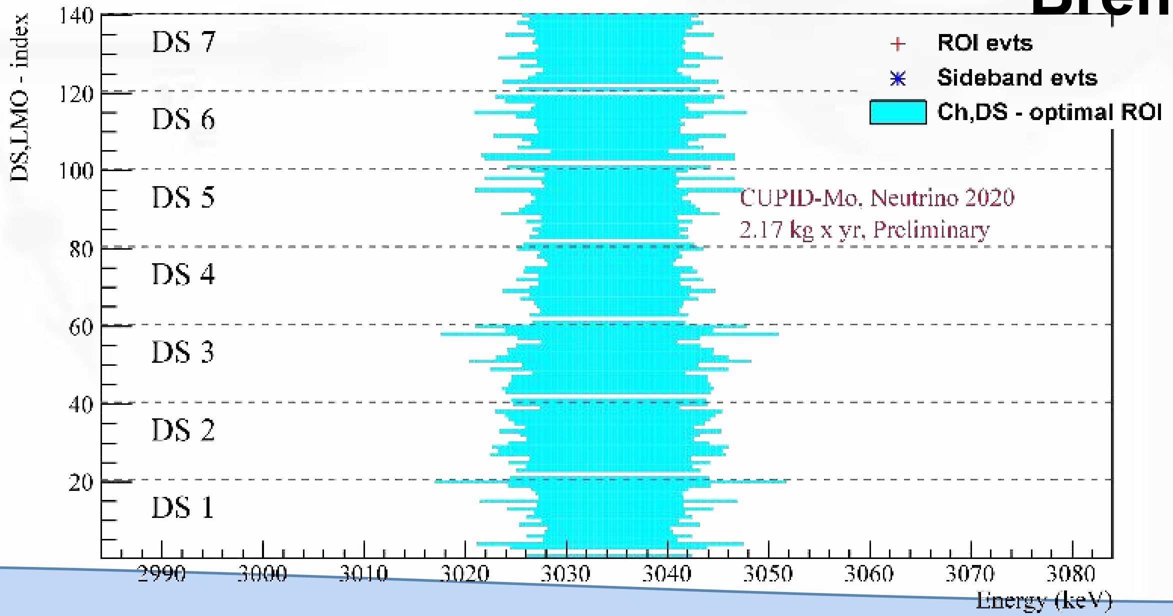


MC simulation of 0ν ββ peak



Detector resolution + **Background index** + **0ν ββ containment Bremsstrahlung escape**

= **ROI**



The CUPID-Mo collaboration

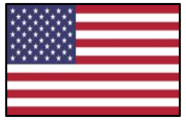
- Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), Orsay, France
- CEA, Direction de la Recherche Fondamentale (CEA/DRF), Gif-sur-Yvette, France
- Institut de Physique Nucléaire de Lyon (IPNL), Lyon, France
- Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, France

- Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

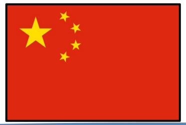
- Istituto Nazionale di Fisica Nucleare (Sezioni di Milano-Bicocca and Roma 1) (INFN), Frascati, Italy
- Laboratori Nazionali del Gran Sasso (LNGS), INFN, L'Aquila, Italy

- Kiev Institute of Nuclear Research (KINR), Kyiv, Ukraine

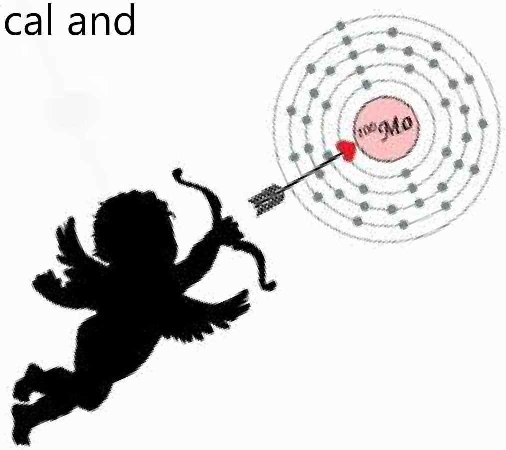
- Joint Institute of Nuclear Research (JINR), Dubna, Russia
- National Research Centre "Kurchatov Institute", Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
- Nikolaev Institute of Inorganic Chemistry (NIIC), Novosibirsk, Russia



- Massachusetts Institute of Technology (MIT), Boston, US
- University of California, Berkeley (UCB/LBNL), Berkeley, US



- Chinese CUPID Institutes (CUPID-China: Fudan, USTC), P.R. China



e⁻
ν̄e
mββ
νe = ν̄e