Annecy, 14/11/2025

The bolometric way to the discovery of neutrinoless double beta decay: CUPID and beyond

Andrea Giuliani

Introduction to double beta decay

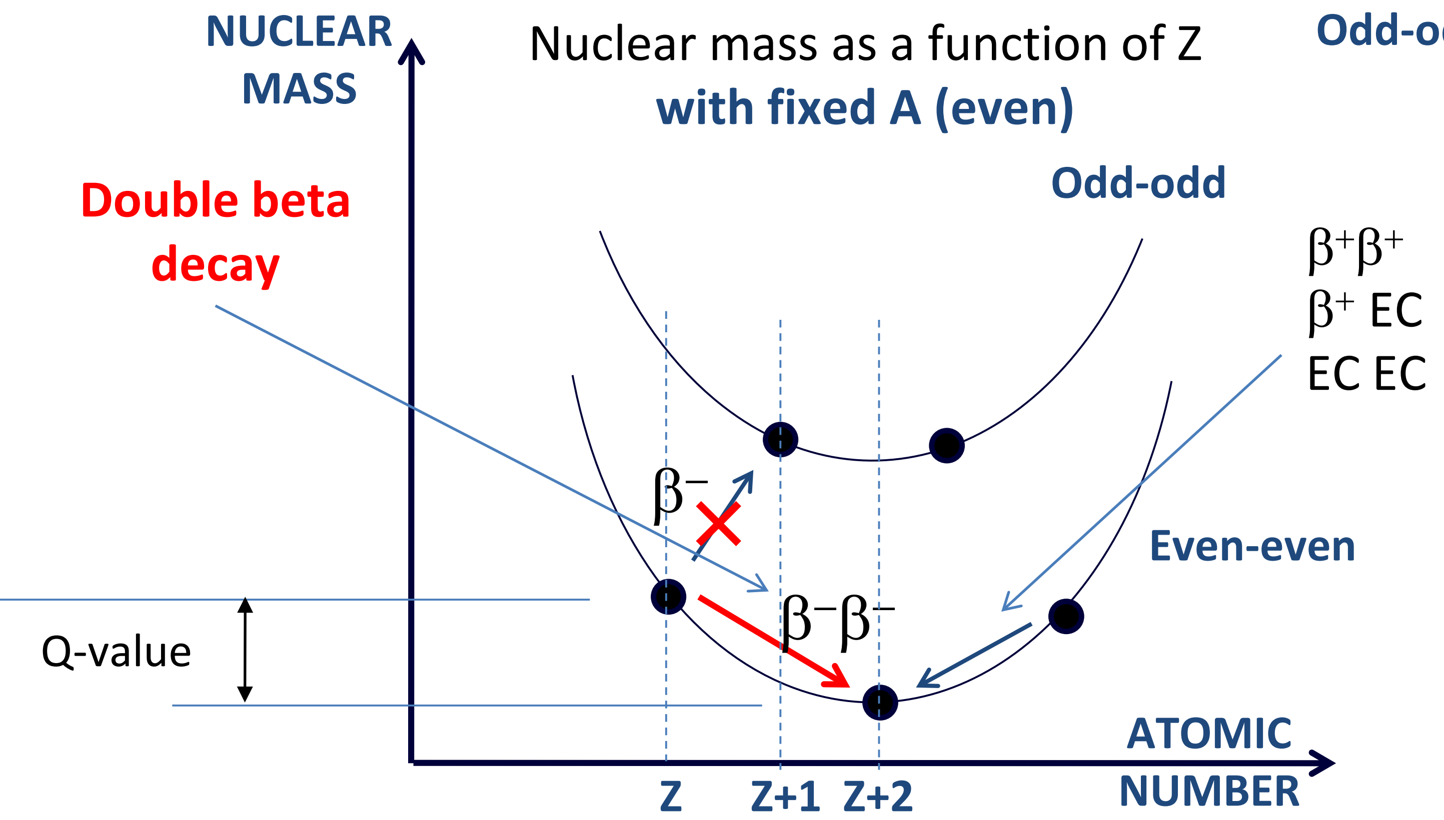
Double beta decay

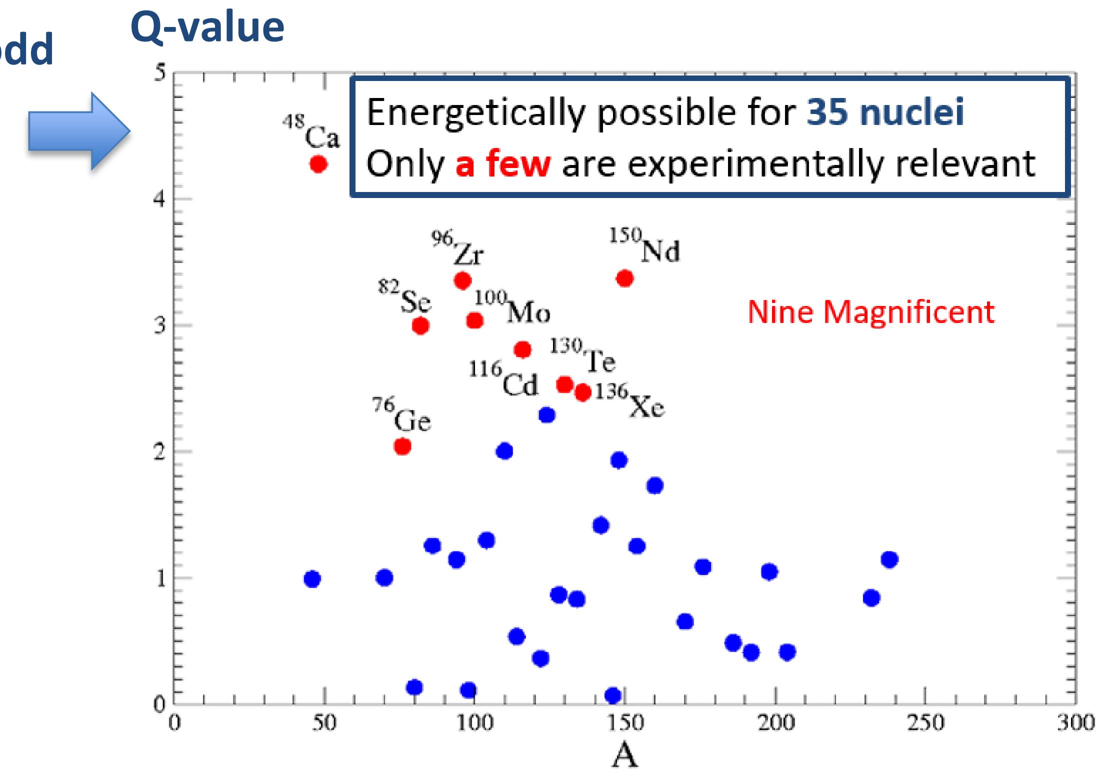
Very rare nuclear transition: (A,Z) $\rightarrow$ (A,Z+2) + 2e$^-$ +2$\bar{\nu}_e$

Weiszaecker's formula for the binding energy of a nucleus

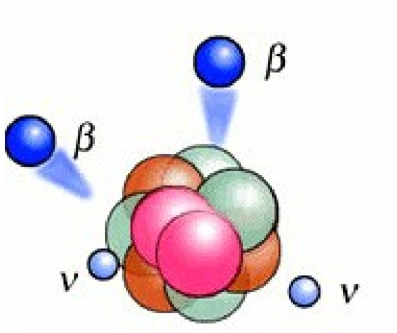
$$E_B(\mathrm{MeV}) = a_v A - a_a (N - Z)^2/A - a_c Z^2/A^{1/3} - a_s A^{2/3} \pm a_\delta/A^{3/4}$$

Even-even (+), Odd-odd (−)





Double beta decay

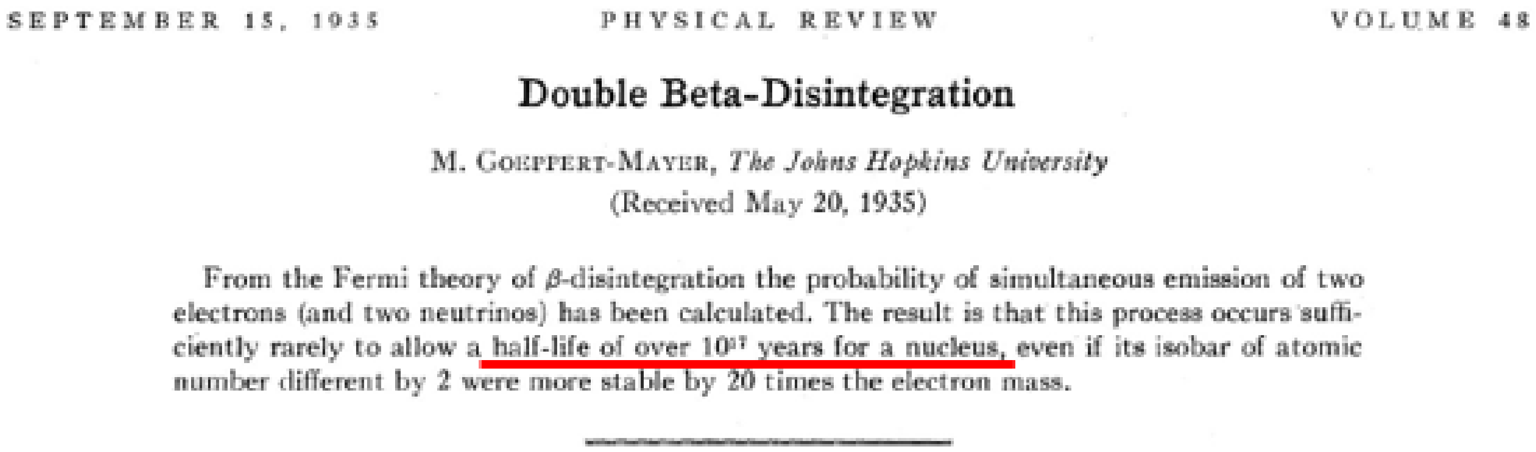


$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \quad 2\nu2\beta$$

The rarest allowed nuclear weak process $\rightarrow$ $\mathbf{T_{1/2} \sim 10^{18} - 10^{24}}$ **y**

Only two years after Fermi's theory of beta decay:

Maria Goeppert-Mayer,
"Double Beta-Disintegration" (1935)



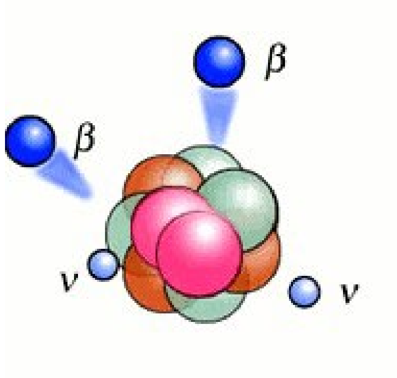
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*
(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

Double beta decay



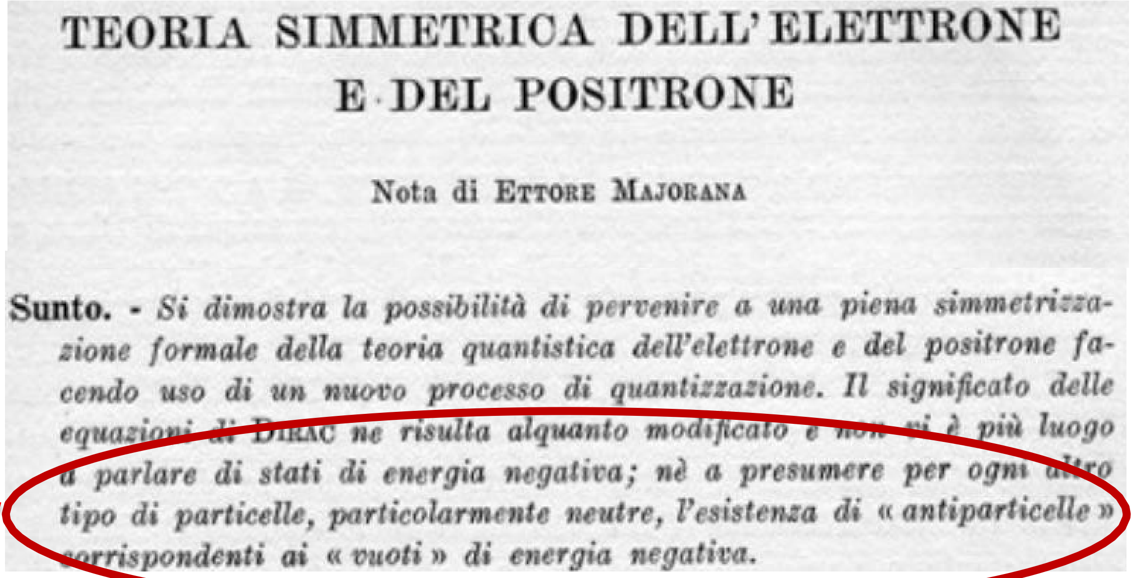
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \qquad 2\nu2\beta$$

The rarest allowed nuclear weak process $\rightarrow$ **$T_{1/2} \sim 10^{18} - 10^{24}$ y**

Ettore Majorana
"No reason to assume the existence of antiparticles for neutral particles"

$$\nu \equiv \overline{\nu}$$

Nuovo Cimento 14(1937)171-184

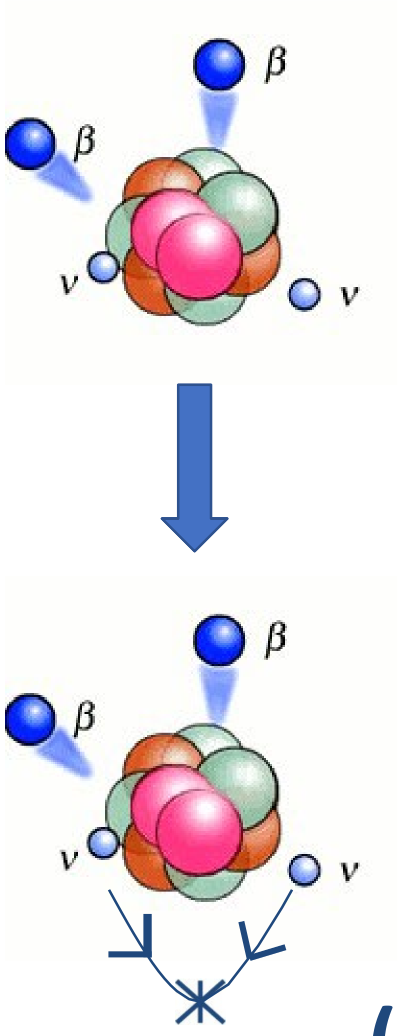


TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

Double beta decay

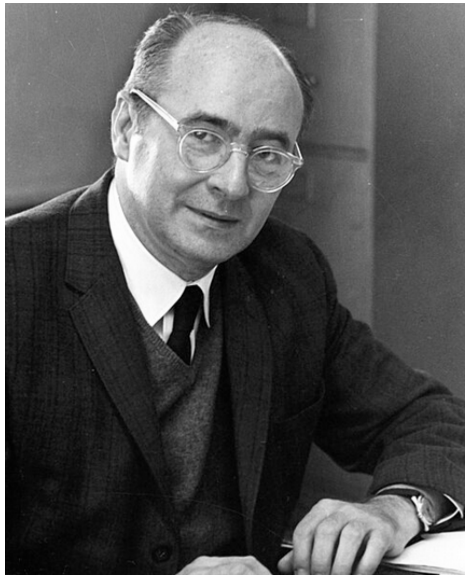


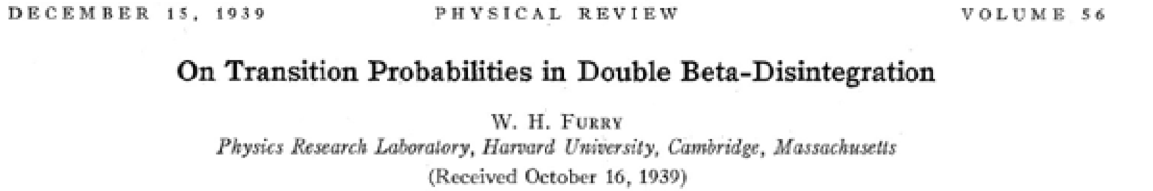
$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$ $2\nu2\beta$

The rarest allowed nuclear weak process $\rightarrow$ $\mathbf{T_{1/2} \sim 10^{18} - 10^{24}}$ **y**

Only two years after Majorana's theory of neutral fermions:

Wendell Furry, "On Transition Probabilities in Double Beta-Disintegration" (1939)





DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. Furry

Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

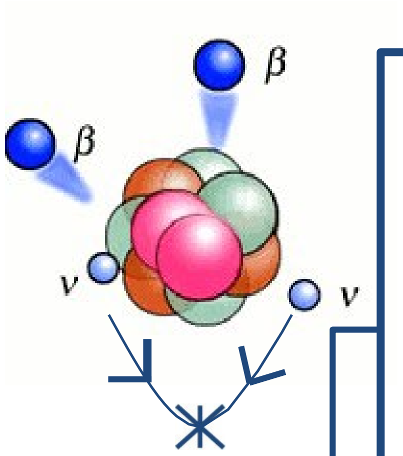
The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger.

$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$ $0\nu2\beta$

Violation of lepton number

$\Delta L = 2$

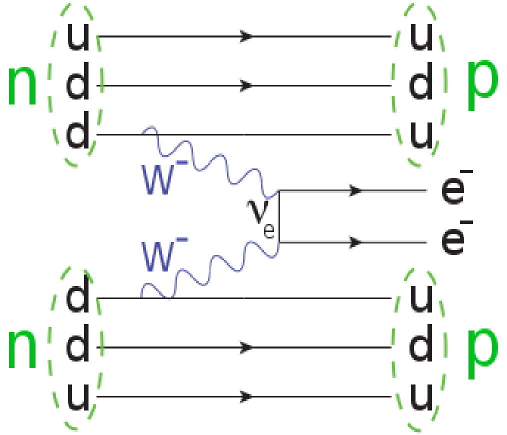
0ν2β : the mechanisms



Minimal straightforward extension of the Standard Model to accommodate neutrino masses

Mass mechanism

0ν2β is mediated by
light massive Majorana neutrinos
(exactly those which oscillate)



Metric to compare experiments and technologies

Two key formulae

0ν2β decay rate

$$1/\tau = G^{0\nu}\, g_A^{4}\, |M^{0\nu}|^2 m_{\beta\beta}^{2}$$

Effective Majorana neutrino mass

$$m_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

Connection with ν oscillation experiments

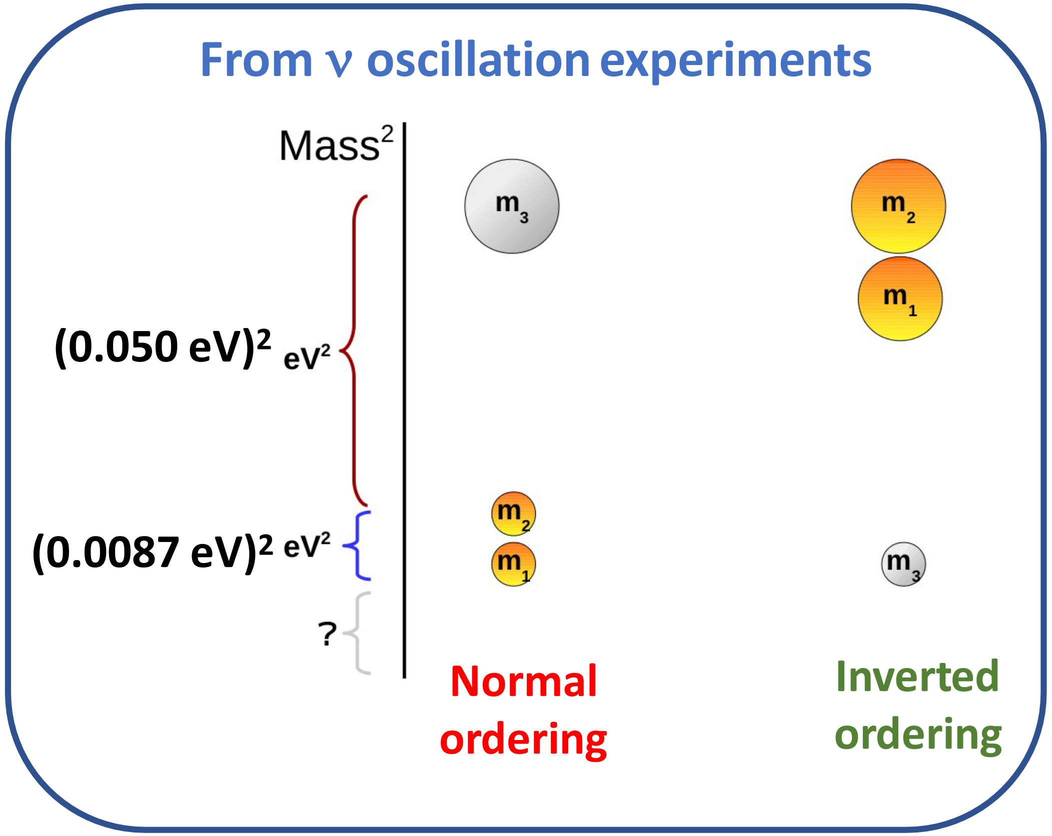
A pletora of other more exotic mechanisms:
Sterile ν, Right currents (W_R), SUSY,…

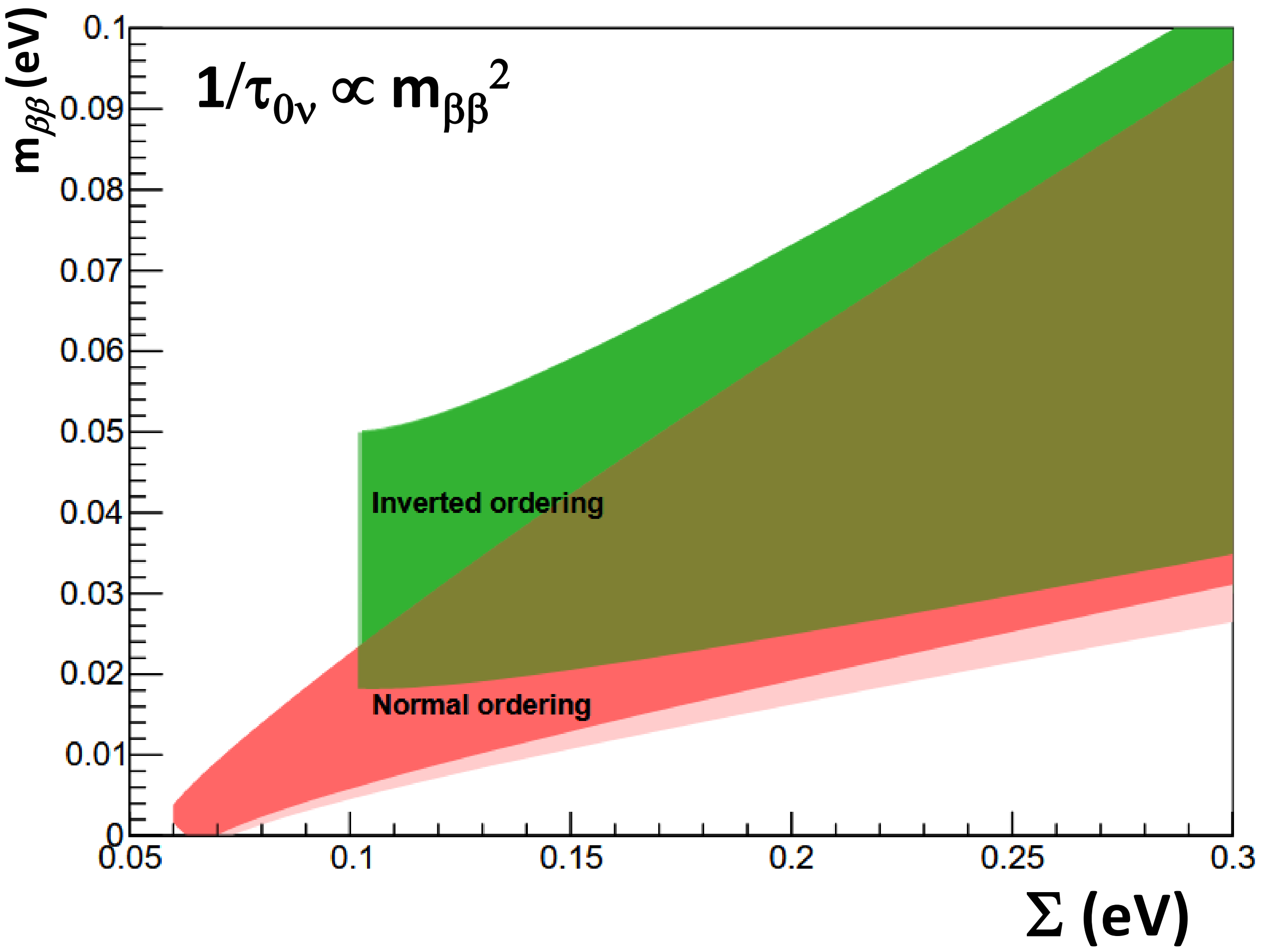
Not necessarily neutrino physics

Light Majorana neutrino exchange: the neutrino mass pattern

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

$m_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3 \,\right| \rightarrow 0\nu 2\beta$

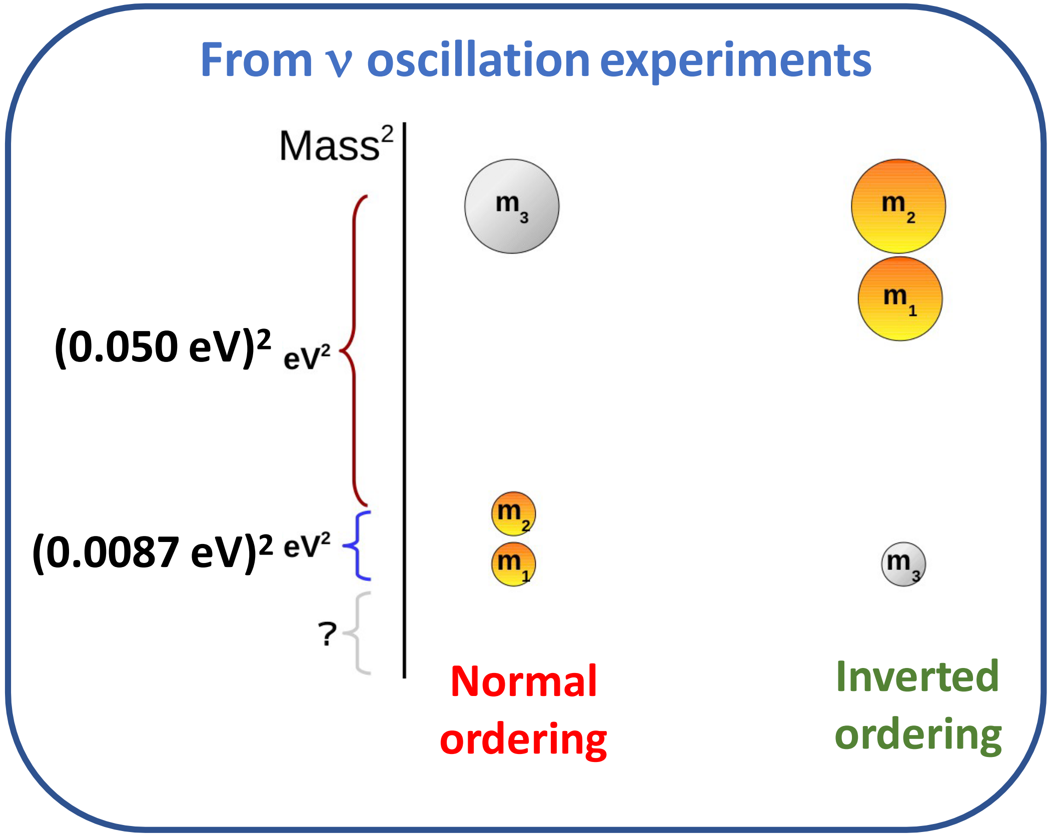


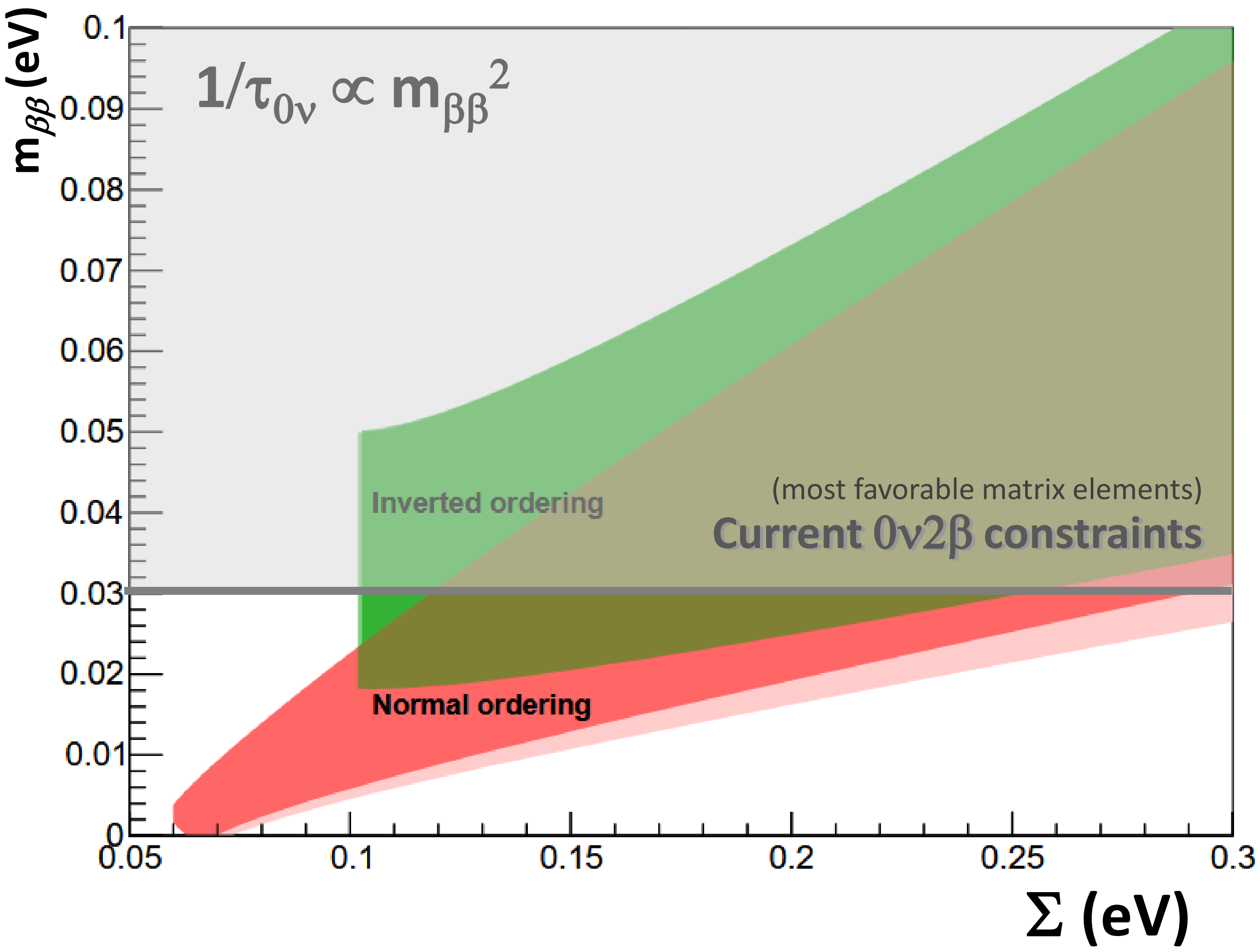


Constraints from 0ν2β

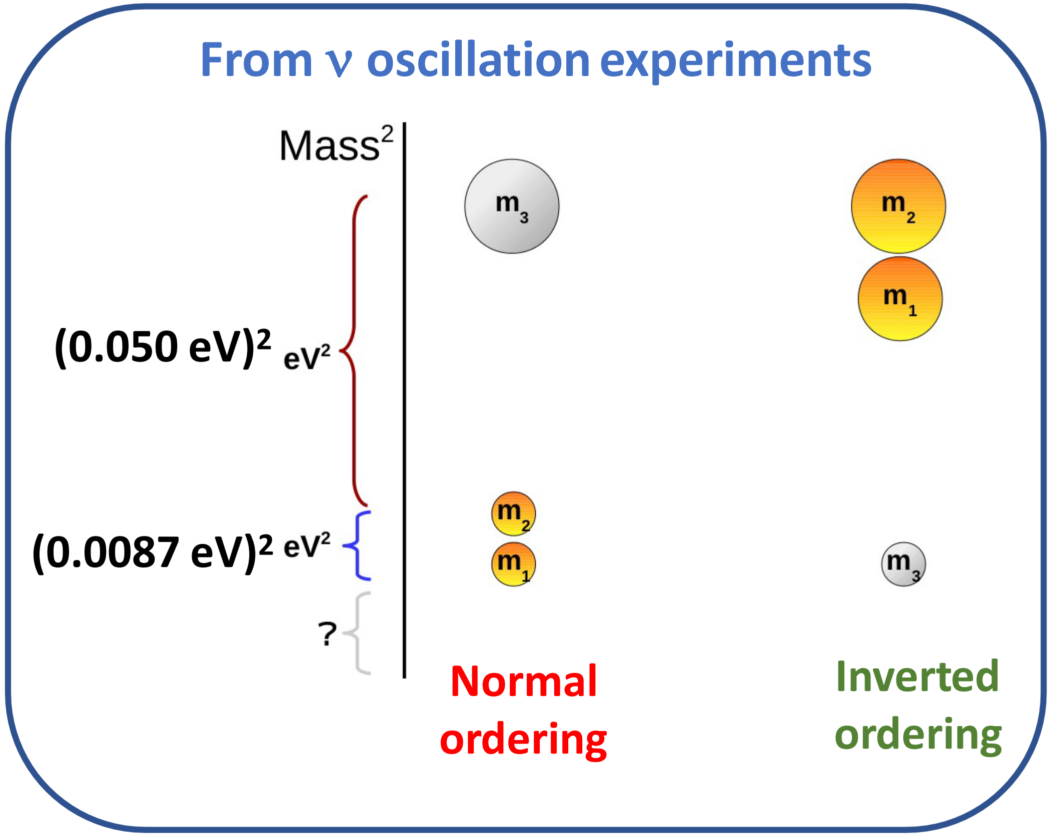
$\Sigma = m_1 + m_2 + m_3$ → Cosmology

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



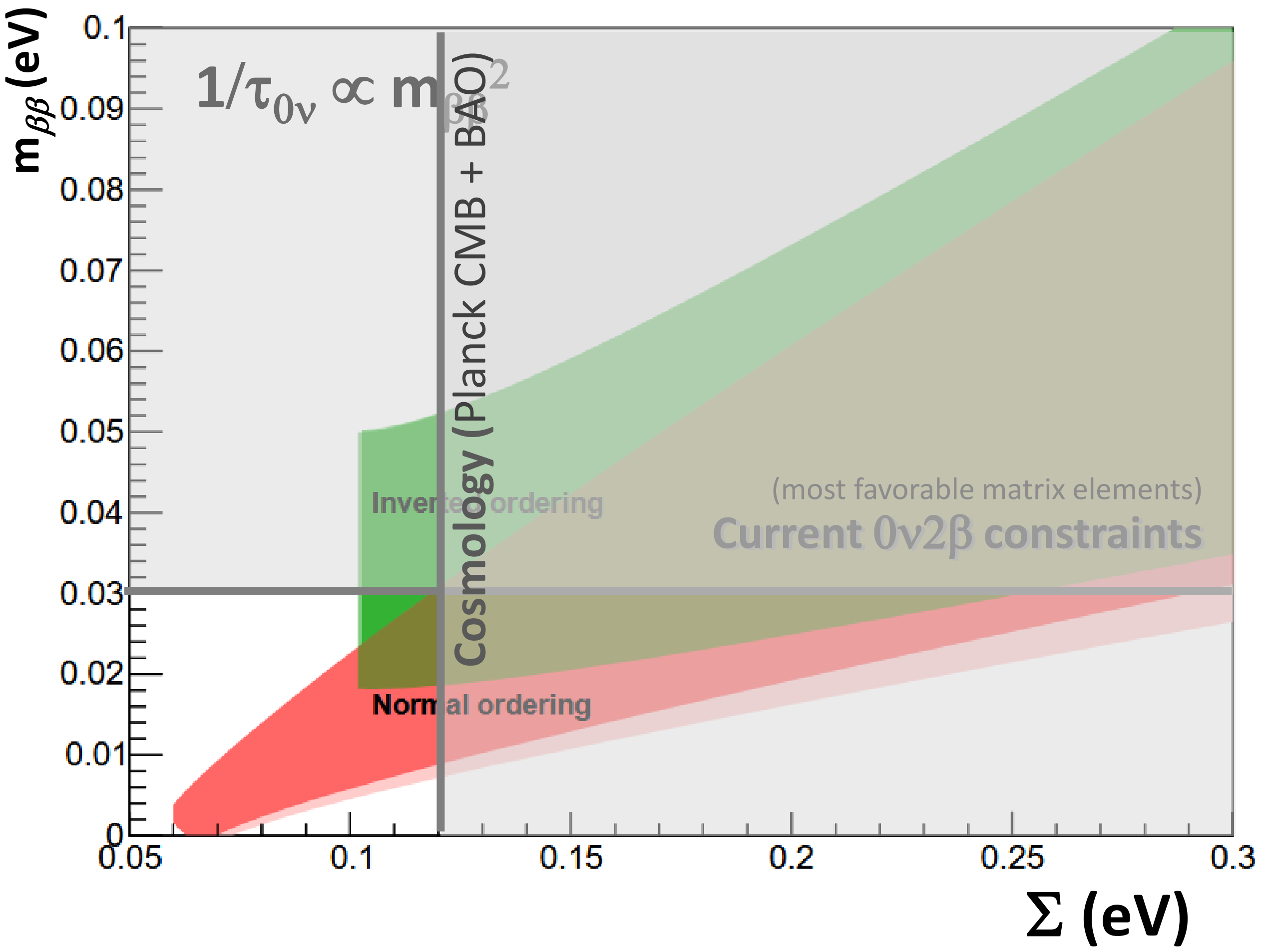


Constraints from cosmology



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

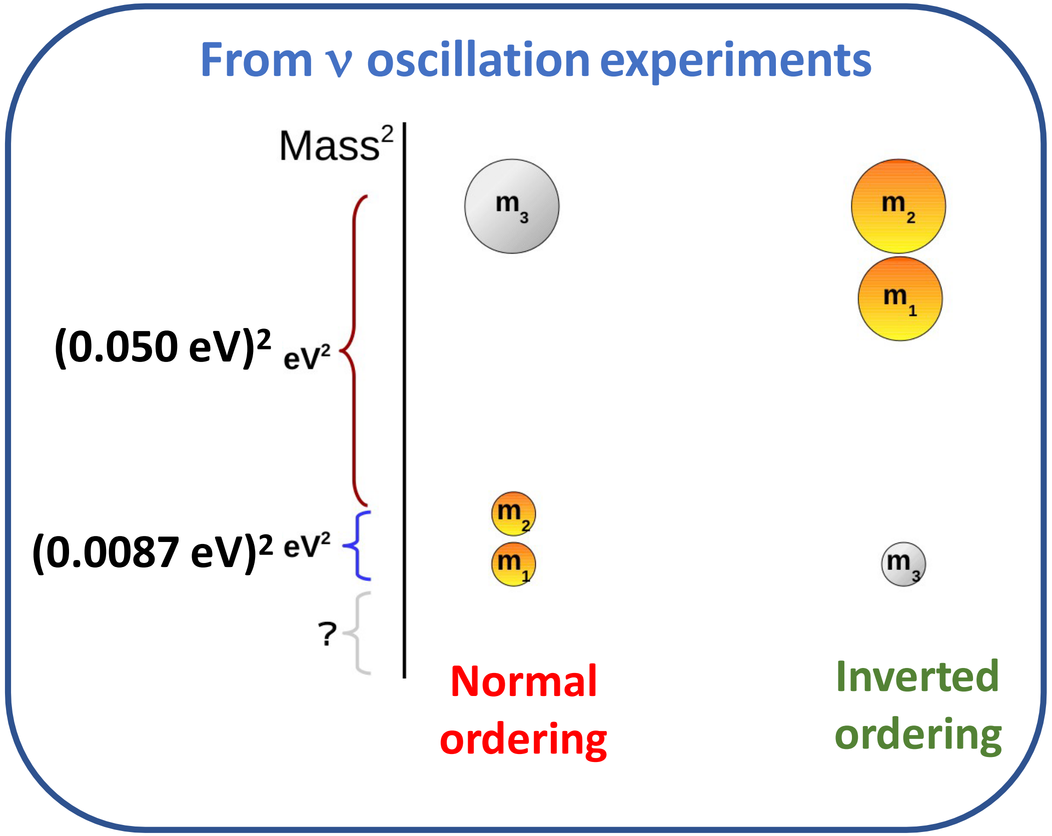
$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$ → 0ν2β

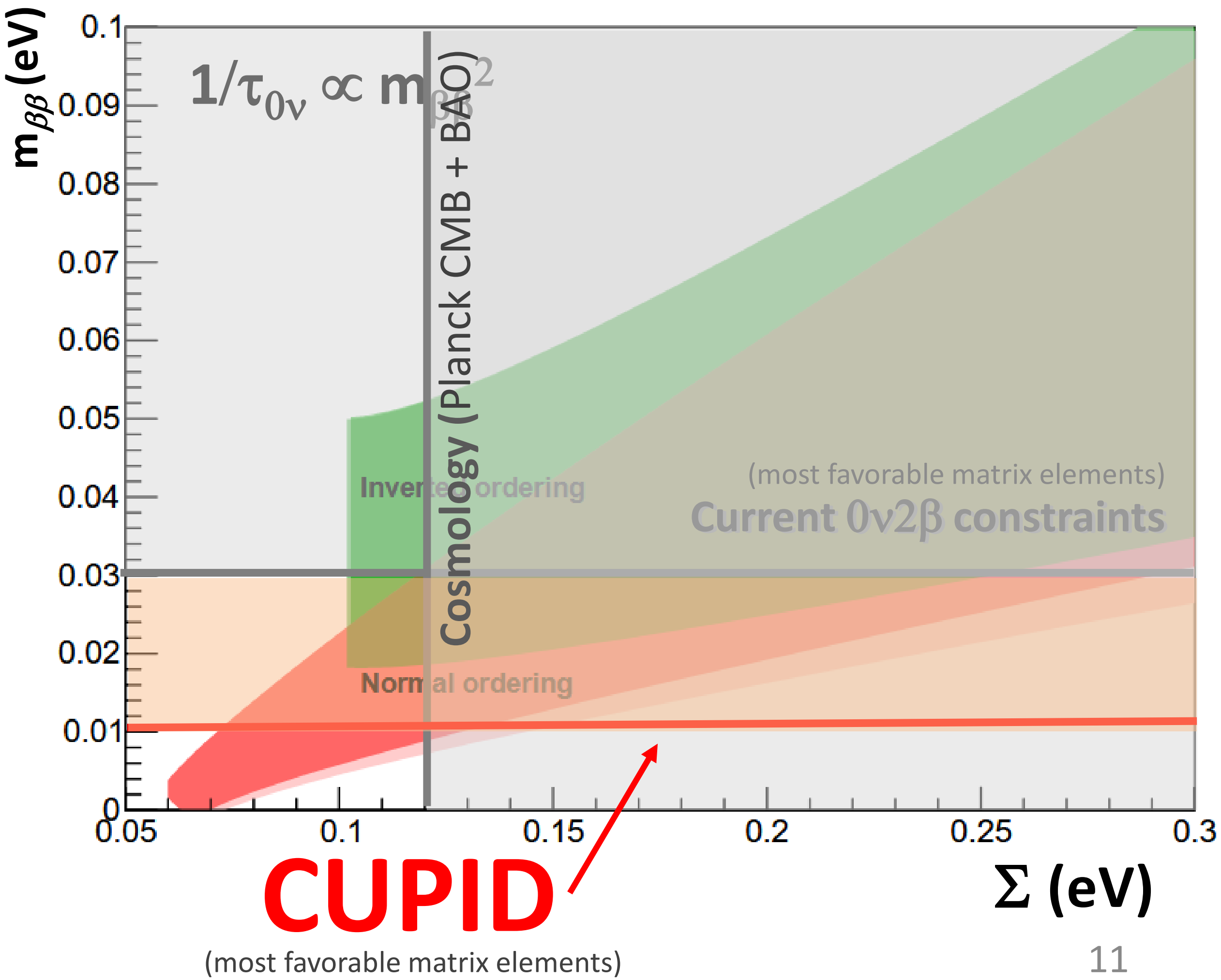


CUPID reach

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

$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3 \right|$ → $0\nu2\beta$





Summary of $0\nu2\beta$ implications

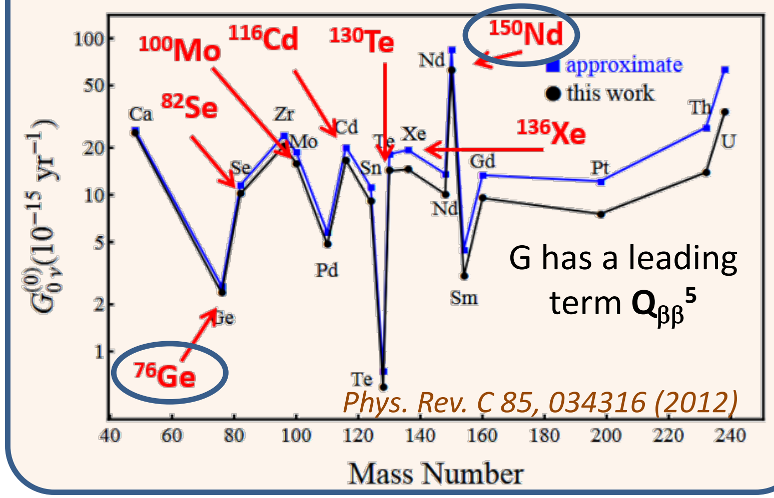
- Violation of **L** and of **B-L**
- Majorana nature of neutrinos $\rightarrow$ New form of matter: **self-conjugate fermions**
- Natural extension of Standard Model, with **Majorana mass term**
- Fix the **neutrino mass scale through** $m_{\beta\beta}$ (not accessible to non-oscillation experiments)
- Explain **smallness of neutrino masses** (See-saw mechanism)
- Can explain **matter / antimatter asymmetry** in the Universe (Leptogenesis)
- Explore other more exotic mechanisms **beyond the Standard Model**

Experimental challenges and methods

Light Majorana neutrino exchange: estimation of the rate

Mass mechanism ➡ $1/\tau = G(Q_{\beta\beta},Z)\, g_A^4\, |M_{nucl}|^2\, m_{\beta\beta}^2$

Phase space: exactly calculable



G has a leading term $Q_{\beta\beta}^5$

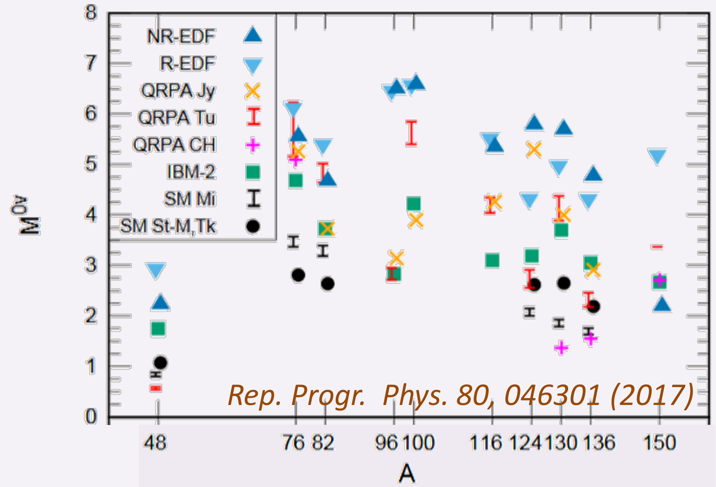
Phys. Rev. C 85, 034316 (2012)

$g_A = \begin{cases} 1.269 & \text{Free nucleon} \\ 1 & \text{Quark} \end{cases}$

$g_{A,eff}$ ~ **0.6 – 0.8** to be taken (« quenching ») to describe β and 2νββ rates with current nuclear models

- Controversial
- Ab-initio calculation with unquenched g_A are required
- Progress ongoing

Nuclear matrix elements: several models



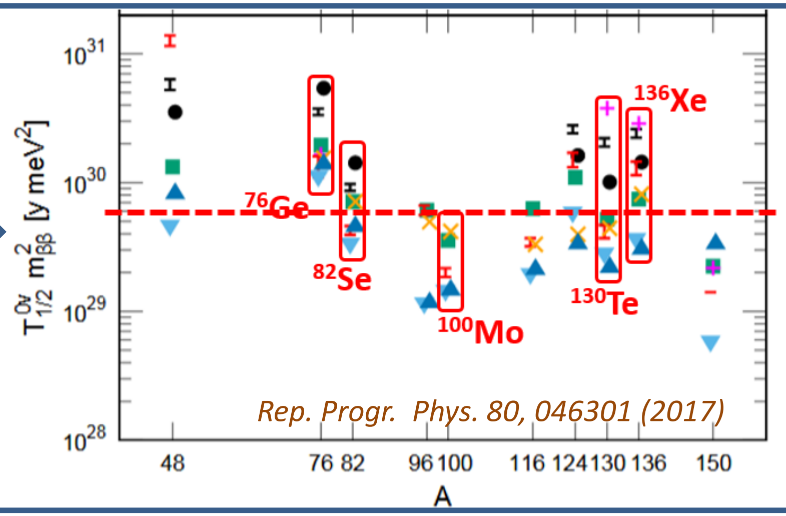
Rep. Progr. Phys. 80, 046301 (2017)

0νββ rate

The 0νββ community still assumes **g_A≈ 1.27** (no quenching) with «traditional models» for M_{nucl}

This point should be revised in the future, after an expected maturation of ab-initio calculations

arXiv:2108.11805

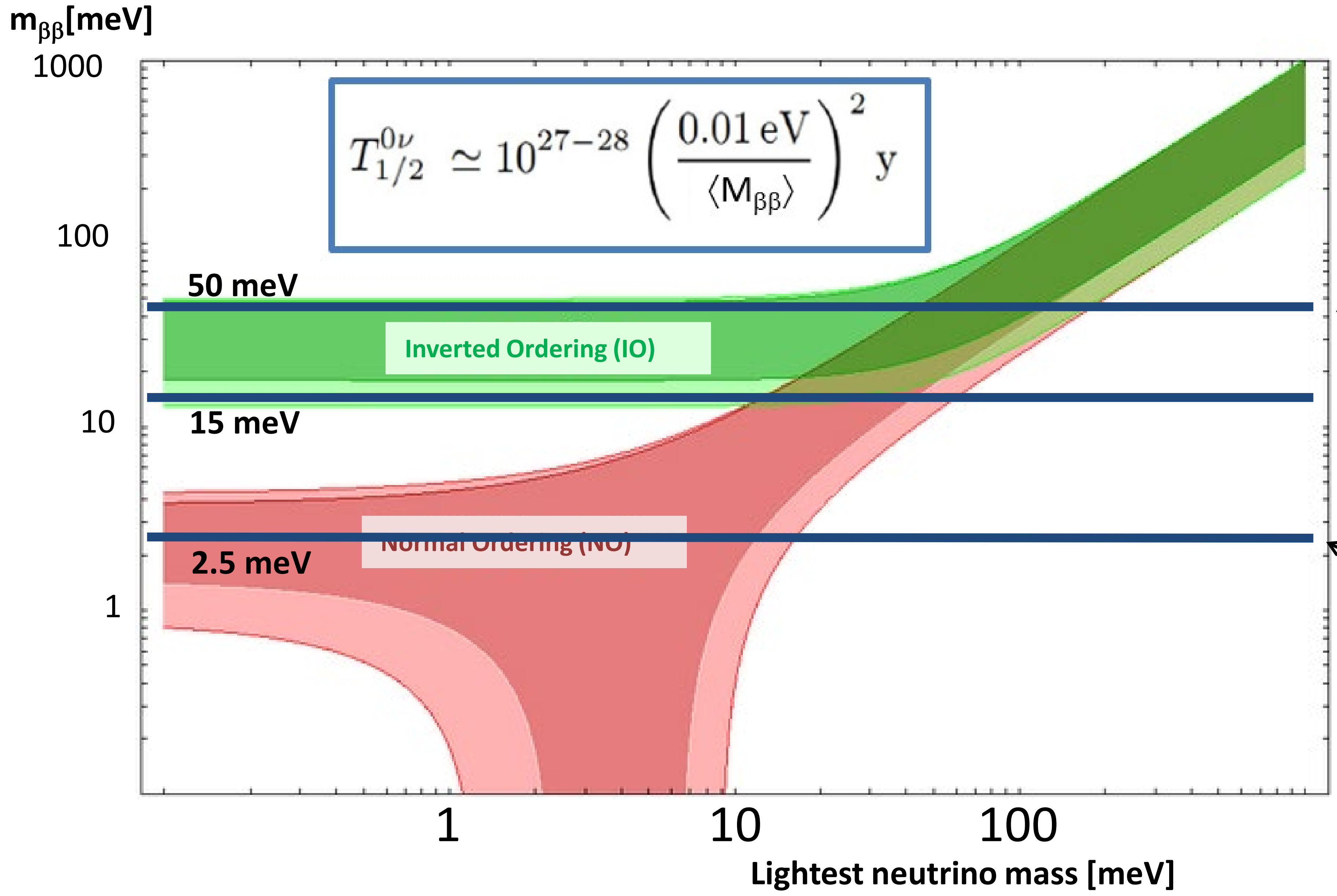


Rep. Progr. Phys. 80, 046301 (2017)

$$T^{0\nu}_{1/2} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \mathrm{y}$$

Working formula for general experiment design

The experimental challenge

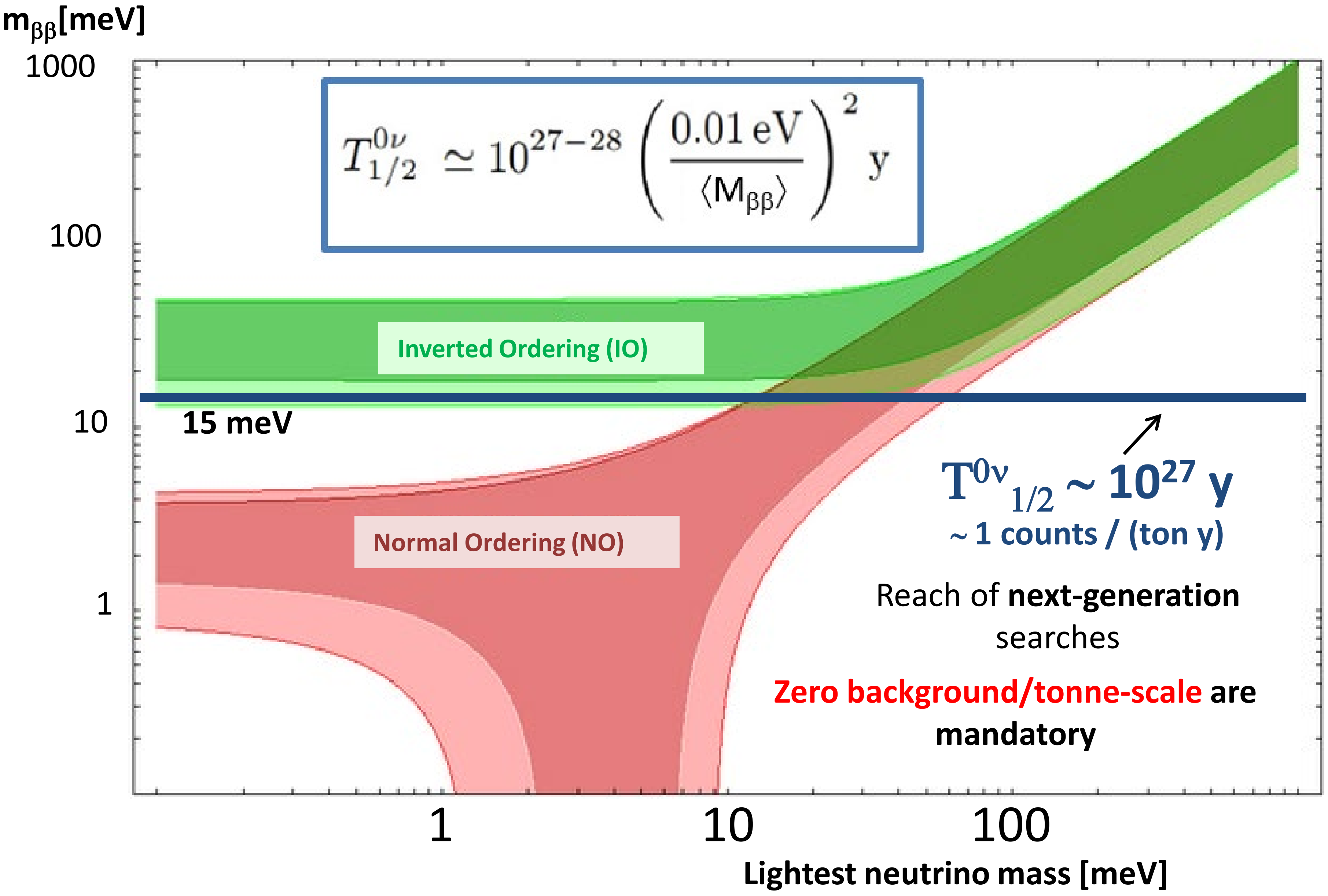


$T^{0\nu}_{1/2} \sim 10^{26}$ y
~ 10 counts / (ton y)
Reach of the **current** searches

$T^{0\nu}_{1/2} \sim 10^{27}$ y
~ 1 counts / (ton y)
Reach of **next-generation** searches

$T^{0\nu}_{1/2} \sim 10^{29}$ y
~ 0.1 counts / (tonne 10y)
Next-to-next generation

The experimental challenge



F: half-life sensitivity

Poisson limit

> 20 background counts

source mass, live time, energy resolution

$F \propto (MT / b\Delta E)^{1/2}$

background index

$b = \frac{\text{background counts @}Q_{\beta\beta}}{M \times \Delta E \times T}$

⇕

Zero background

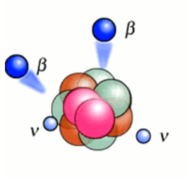
$b \times M \times \Delta E \times T << 1$

$F \propto MT$

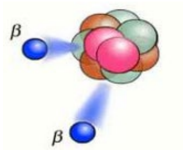
Searching for 0ν2β

Standard and new-physics channels:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ➡ **2ν Double Beta Decay** (2ν2β)
allowed by the Standard Model
already observed – **τ ~10^{19} – 10^{24} y**



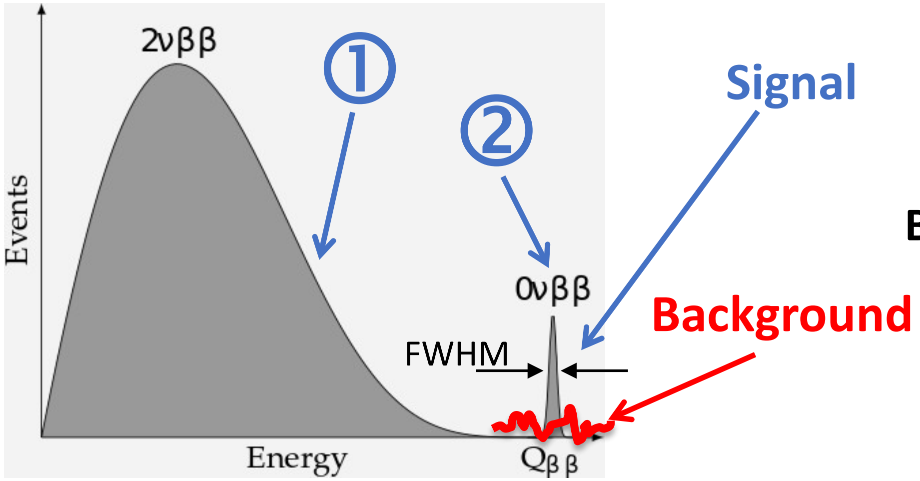
② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ➡ **Neutrinoless**
Double Beta Decay (0ν2β)
never observed **τ > 10^{26} y**



Experimental signatures based on the

Sum-energy spectrum of the two electrons

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



Energy resolution
FWHM
[keV]

Background index b:

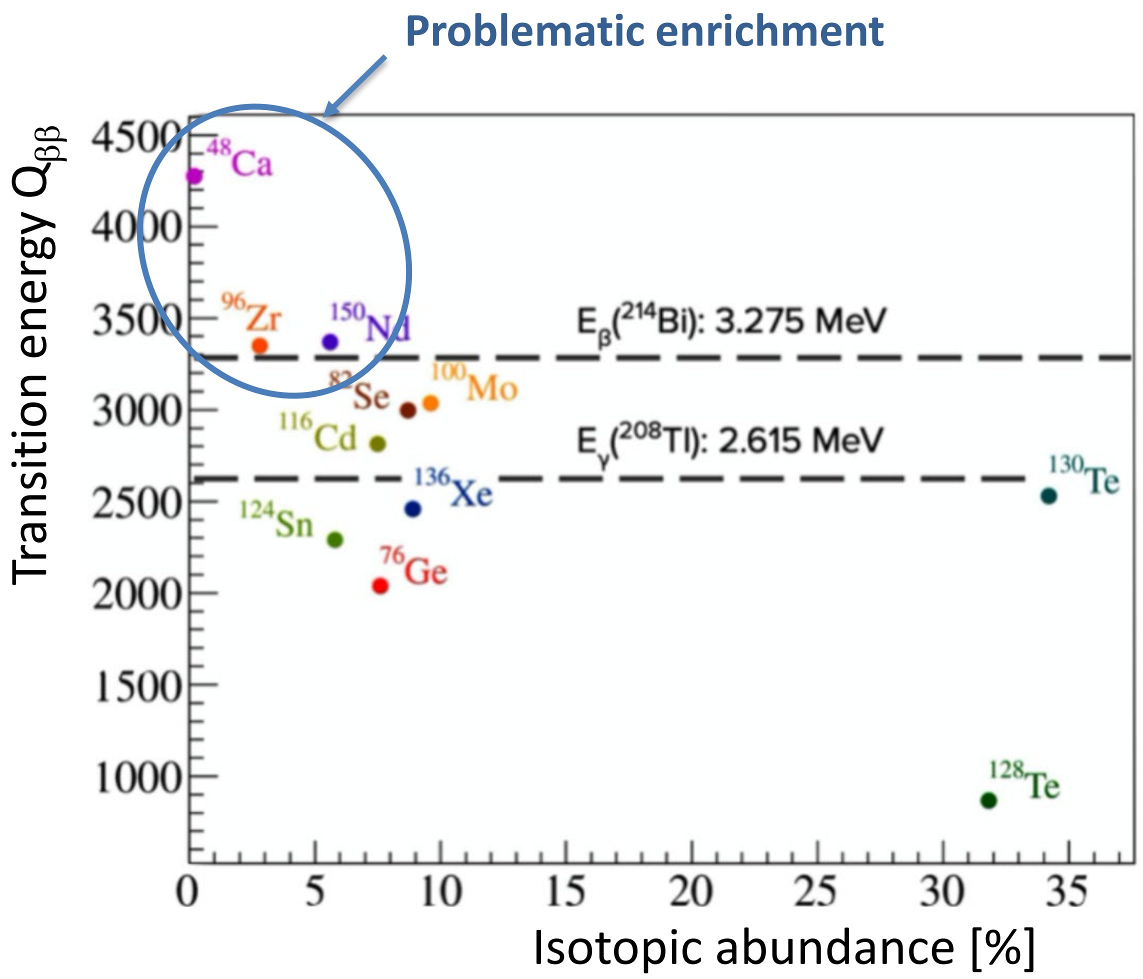
$$\frac{\text{Counts}}{M \cdot T \cdot \Delta E}$$

[counts/(keV·kg·y)]

Searching for 0ν2β

- **High isotopic abundance** (I.A.) and/or **easy enrichment**
- **High $Q_{\beta\beta}$**
  - Larger phase space: $G(Q,Z) \propto Q^5$
  - Easier background control

Compatibility with a beneficial **detection technique**
- **High energy resolution**
- **Background identification**
- **Efficiency and scalability**

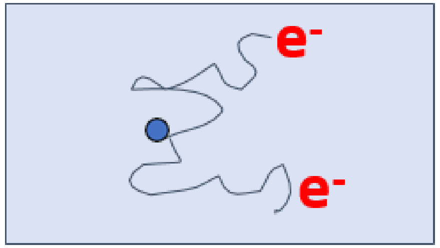


Searching for $0\nu2\beta$

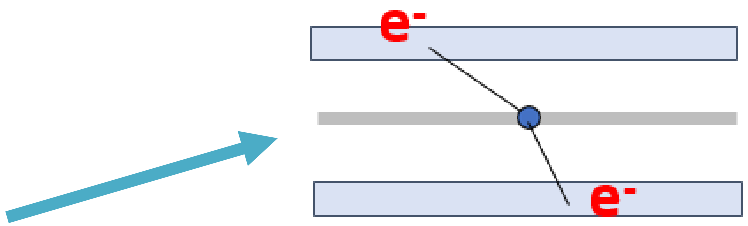
Requests for the source

① **Large source** → tonne scale → > 10^{27} nuclei

② **Maximize efficiency**
→ The option in which the source is separated from the detector is abandoned for next-generation experiments



Source ⊆ Detector



Source ⊈ Detector

However, this option may be interesting in case of discovery to investigate the mechanism of $0\nu\beta\beta$

SuperNEMO demonstrator, Modane

Requests for the background

Generic measures as underground operation, shielding (passive and active), radiopurity of materials, vetos are common to $0\nu2\beta$ and other rare event search

Specific desirable features for $0\nu\beta\beta$

- High energy resolution
- Particle identification
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface vs. bulk events
- Fiducial volume / Active shielding
- Final-state nucleus identification

Searching for $0\nu2\beta$: complementary/competing technologies

Liquids and gases

① **Source dilution in a liquid scintillator**

KamLAND-Zen (^{136}Xe) – SNO+ (^{130}Te)

→

- Re-use of existing infrastructures
- Large amount of isotopes (multi-ton)
- Isotope dilution (a few %)
- Energy resolution ~ 10 % FWHM
- Rough space resolution

② **TPCs**

EXO-200 – NEXT – nEXO (^{136}Xe)

→

- Large amount of isotopes (multi-ton)
- Full isotope concentration
- Energy resolution ~ 1 % - 2 % FWHM
- Event topology

Single crystals

③ **Semiconductor detectors**

GERDA – LEGEND (^{76}Ge)

④ **Bolometers**

CUORE (^{130}Te) – AMoRE – CUPID (^{100}Mo)

→

- Crystal array (~1 ton scale in total)
- (Almost) full isotope concentration
- Energy resolution ~ 0.1 % - 0.2 % FWHM
- Particle identification
- Pulse shape discrimination

Experimental status

KamLAND-Zen 800 - $T_{1/2} > 3.8\times10^{26}$ y
arXiv:2406.11438 (2024)

GERDA - $T_{1/2} > 1.8\times10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

EXO-200 - $T_{1/2} > 3.5\times10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

MAJORANA dem. - $T_{1/2} > 8.3\times10^{25}$ y
Phys. Rev. Lett. 130, 062501 (2023)

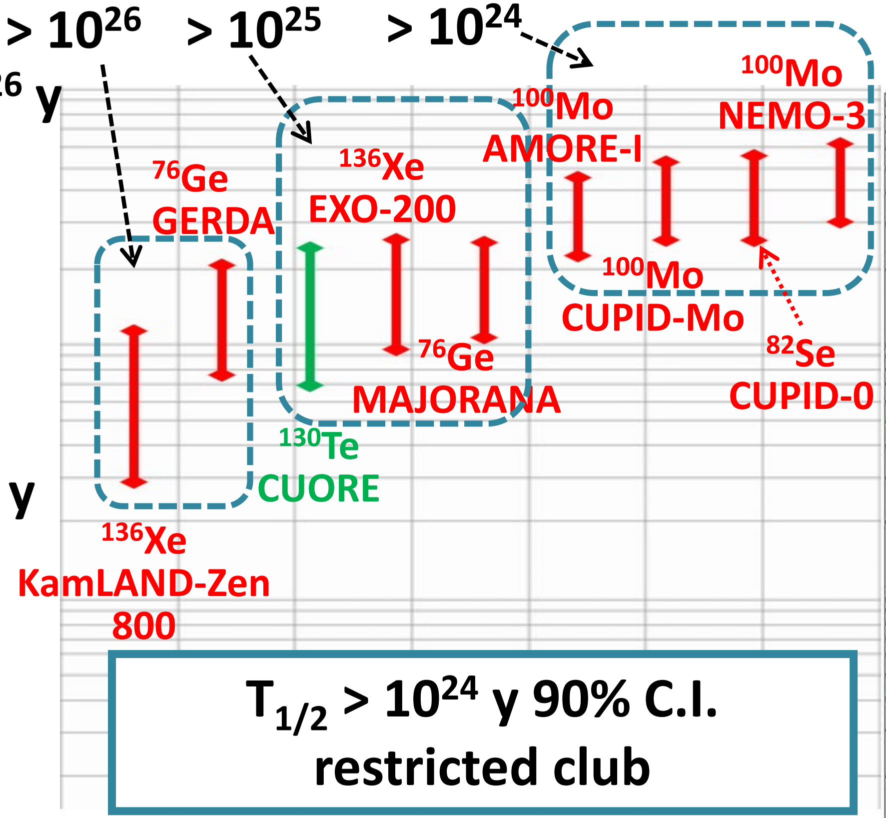
CUORE - $T_{1/2} > 3.5\times10^{25}$ y
TAUP 2025 (2025)

CUPID-0 - $T_{1/2} > 4.6\times10^{24}$ y
Phys. Rev. Lett. 129, 111801 (2022)

AMORE-I - $T_{1/2} > 2.9\times10^{24}$ y
Phys. Rev. Lett. 134, 082501 (2025)

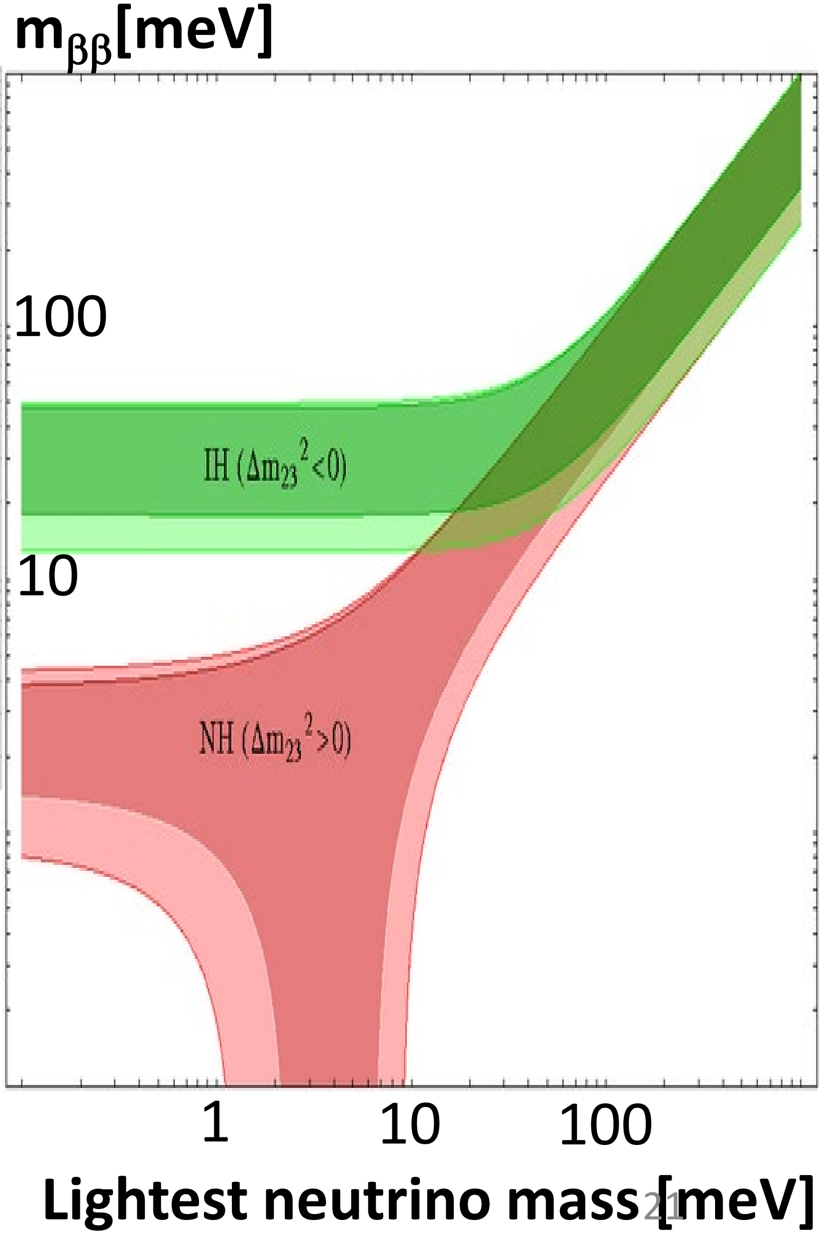
CUPID-Mo - $T_{1/2} > 1.8\times10^{24}$ y
Eur. Phys. J. C 82, 1033 (2022)

NEMO-3 - $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)



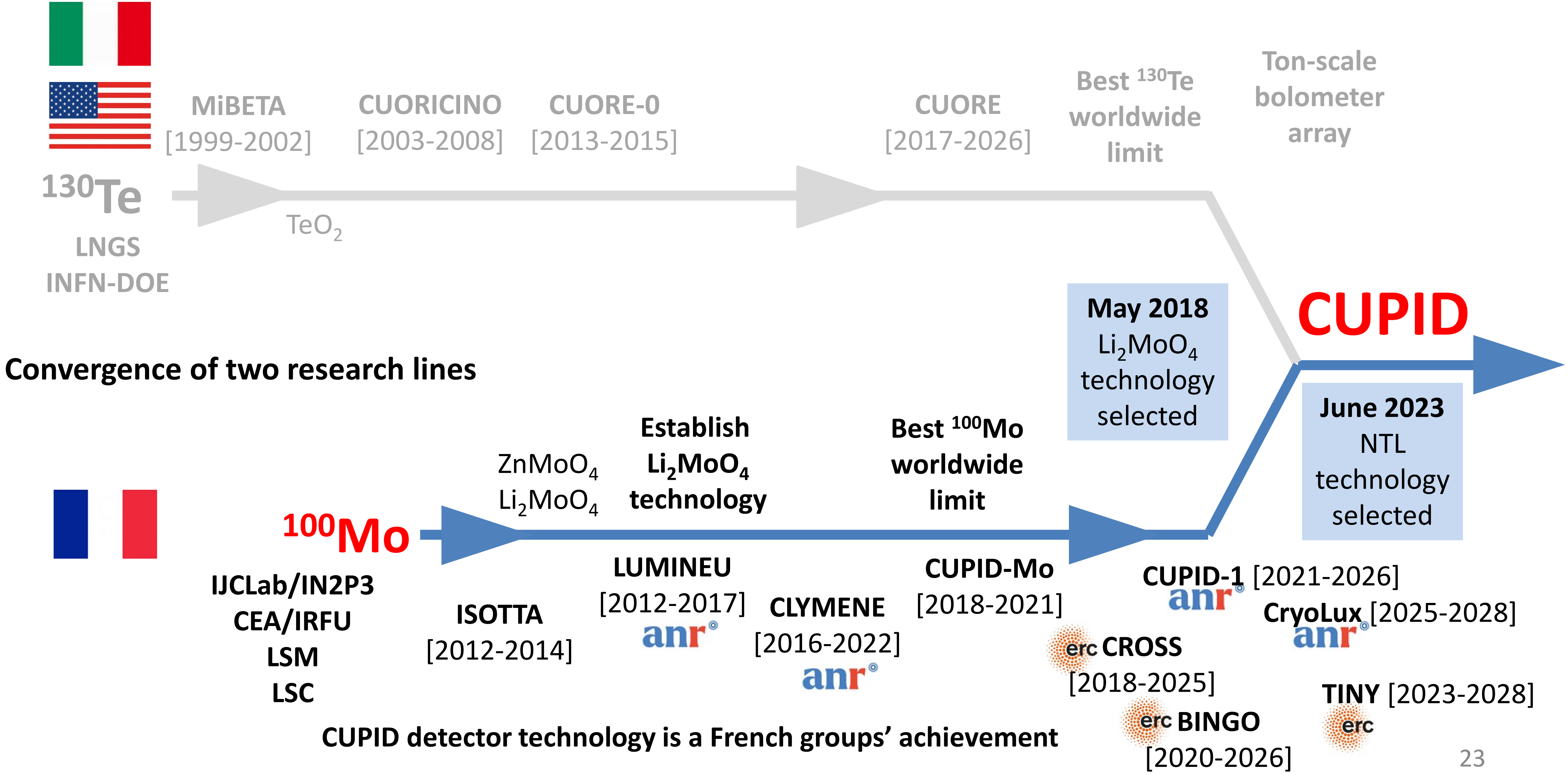
All experiments stopped except
CUORE
(expected end: mid-2026)

Next generation!

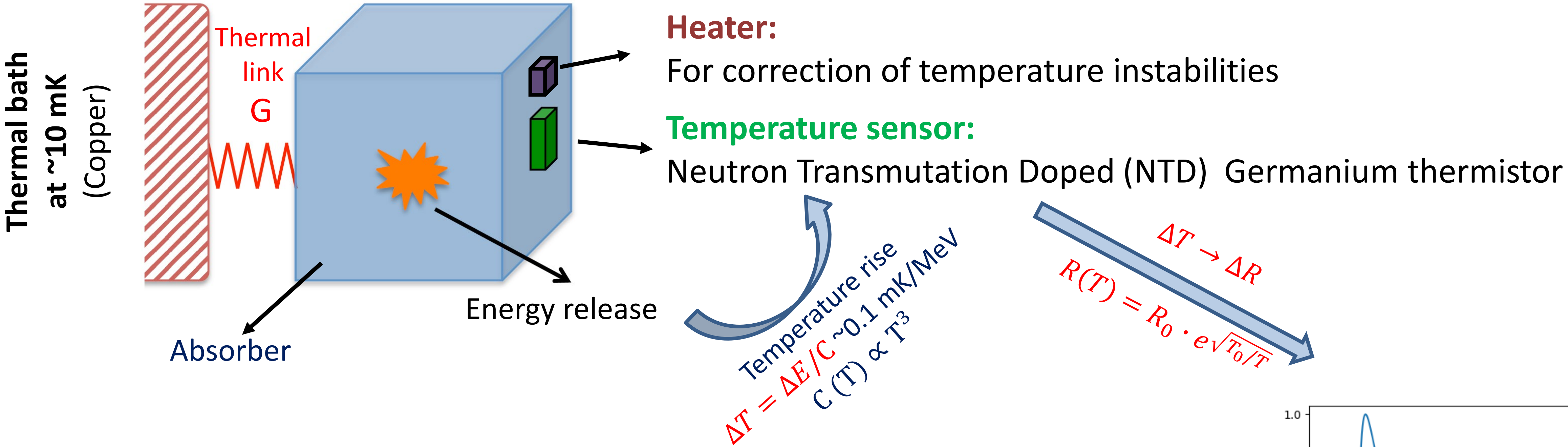


CUPID

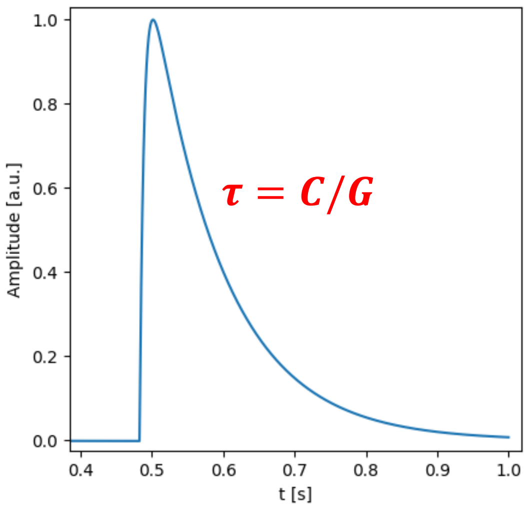
CUPID's origin and history



Bolometric technique



Bolometric detector properties match well the required features for 0ν2β search



- Good energy resolution ~ 5-10 keV at 2.5 MeV
- Large flexibility in material choice
- Source = detector: high efficiency

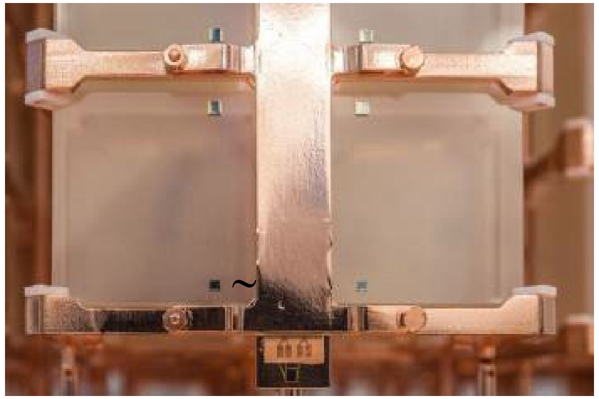
CUORE in a nutshell

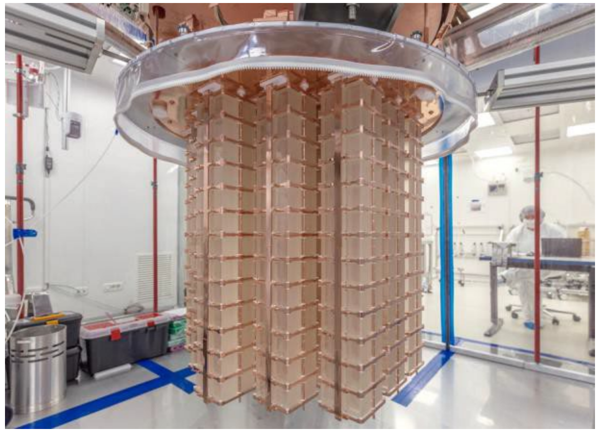
CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy) at **~12-15 mK**

The largest bolometric experiment ever

- 988 crystals 5x5x5 cm, closely packed arranged in 19 towers of 13 floors each
- 742 kg (**206 kg** of **^{130}Te**)
- Start data taking: 2017
  Stable data taking: from **2019**
- Background at $Q_{\beta\beta}$ (2527 keV)
  1.42×10^{-2} counts/(keV·kg·y)
- Energy resolution at $Q_{\beta\beta}$
  7.3 keV FHWM

Nature 604 (2022) 53-58





One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Exposure for the current limit: **2039 kg·y (> 2.8 tonne·y collected)**
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 3.5×10^{25} y**
  → **$m_{\beta\beta}$ < 70 – 250 meV** Preliminary
- Continue data taking until final goal:
  3 tonne·yr TeO_2 exposure
  → **mid 2026**

A. Campani, TAUP 2025

CUORE is not background free

→ **~70 counts/y in a ROI size FWHM energy resolution**, dominated by **surface α background**

CUORE → CUPID

Three important messages from CUORE

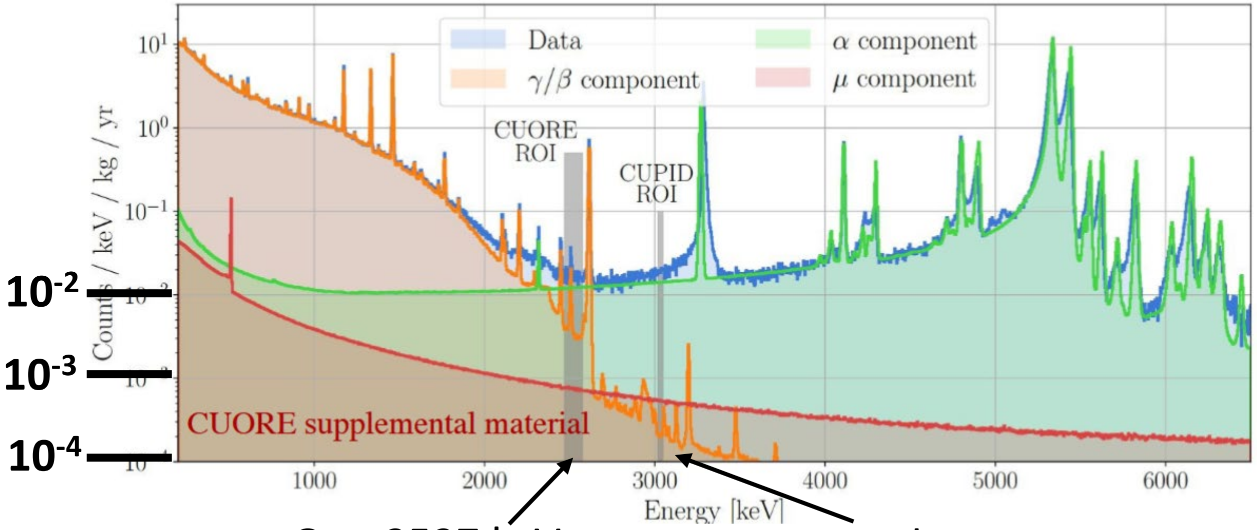
1. **A tonne-scale bolometric detector** is technically feasable
2. **Analysis of ~1000 individual bolometers** is handable
3. **An infrastructure to host a bolometric next-generation $0\nu2\beta$ experiment exists** and will be available at the end of the CUORE physics program (30/6/2026)

CUPID (CUORE Upgrade with Particle ID) is a future $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**

CUPID background goal:
b ~ 1×10^{-4} counts/(keV·kg·y)

CUORE background model

b
[counts/(keV· kg· y)]



$Q_{\beta\beta}$: 2527 keV (^{130}Te)

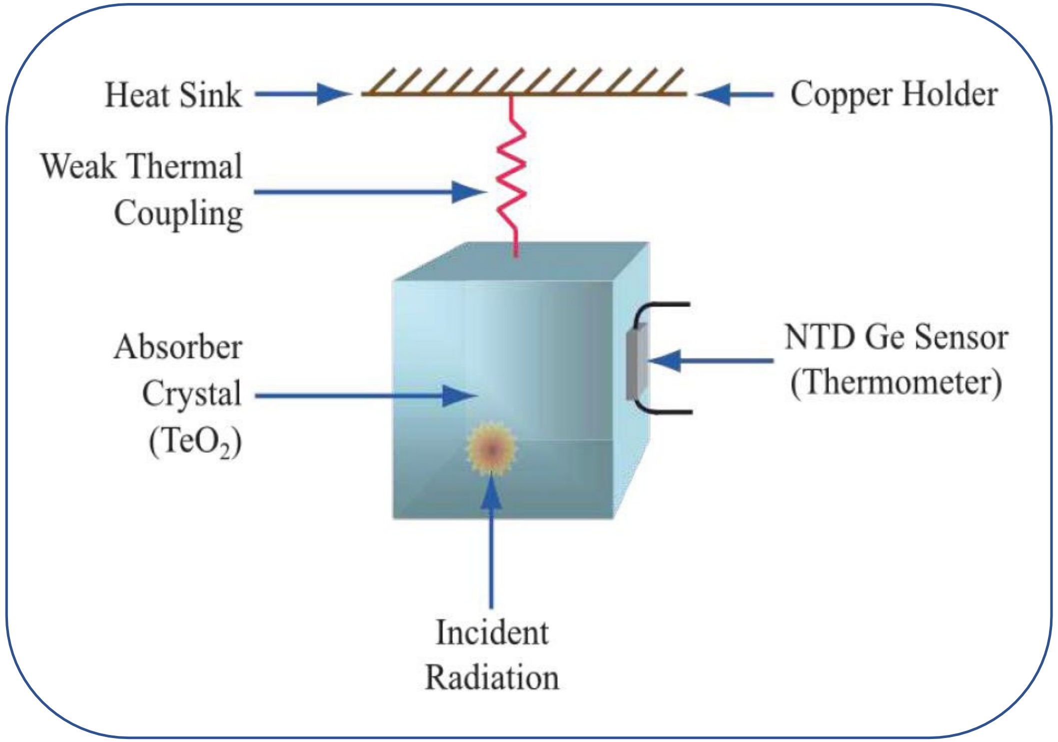
$Q_{\beta\beta}$: 3034 keV (^{100}Mo)

- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**

  → $Q_{\beta\beta}$: 2527 keV (^{130}Te) → 3034 keV (^{100}Mo)
- Increase isotope mass by **enrichment** (natural isotopic abundance: 9.7%)

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)

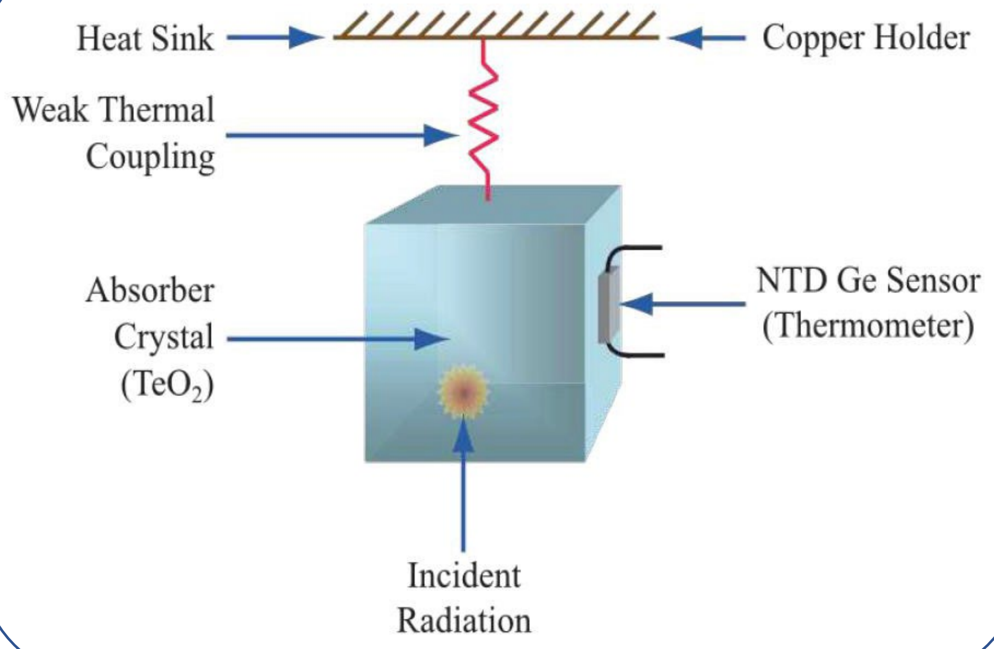


No PID

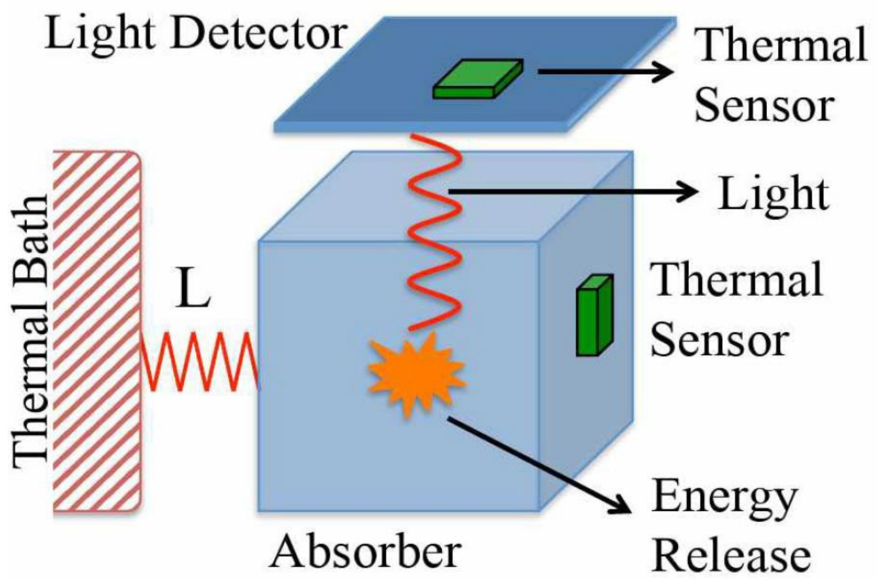
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



No PID
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α background

γ background

CUPID rationale

CUORE ^{130}Te
pure thermal detector
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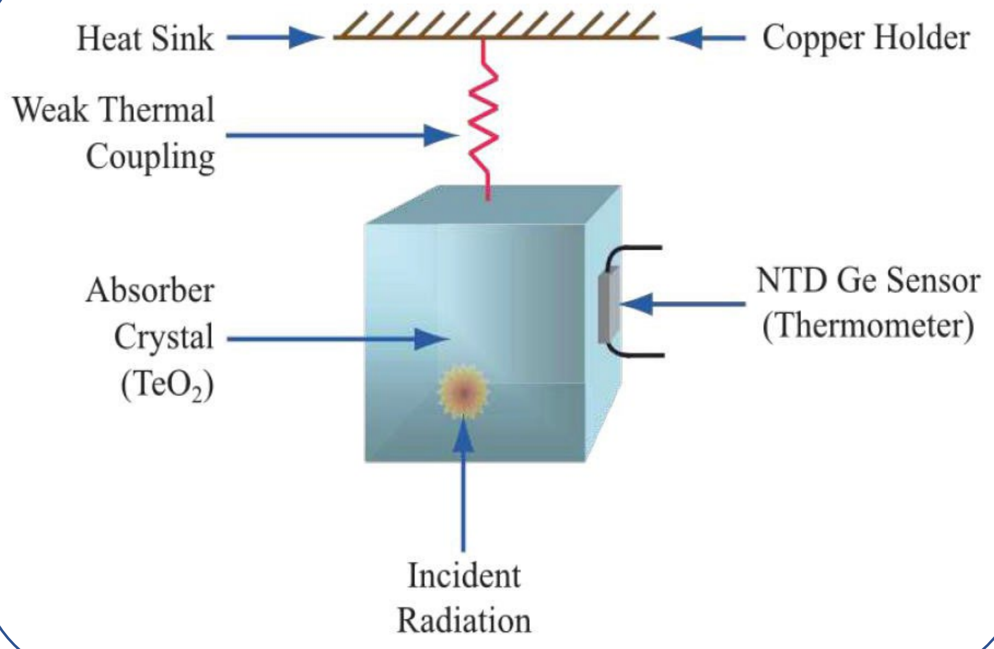

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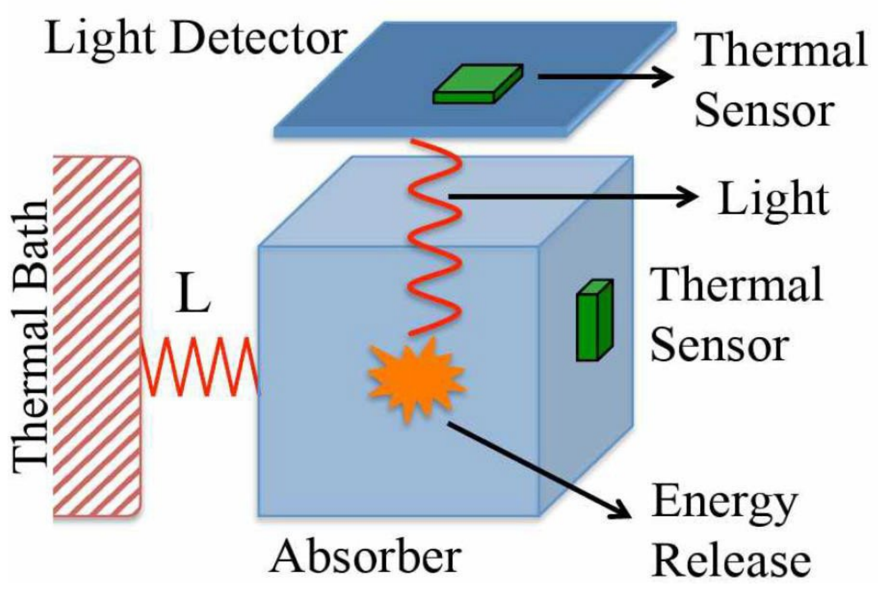

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~~α background~~ ← **PID**

γ background

CUPID rationale

CUORE ^{130}Te
pure thermal detector
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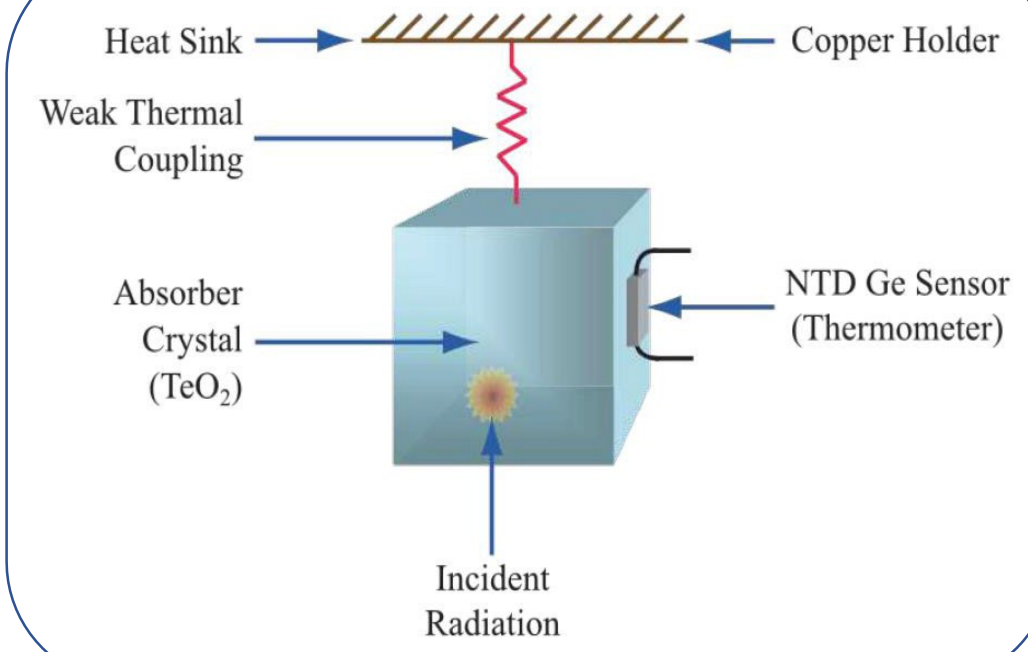

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heat + light
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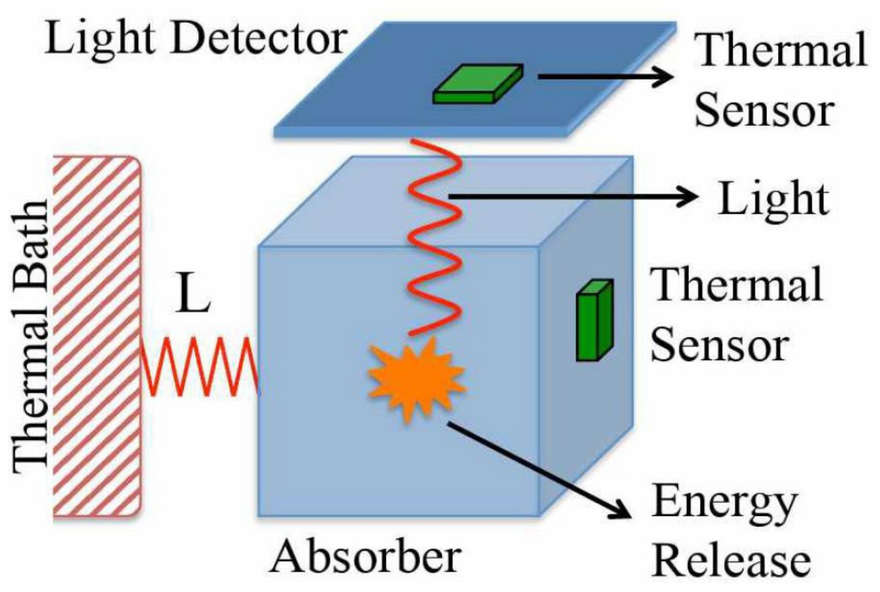
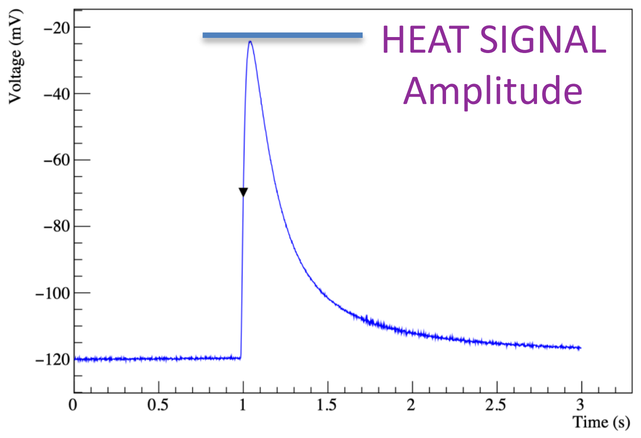


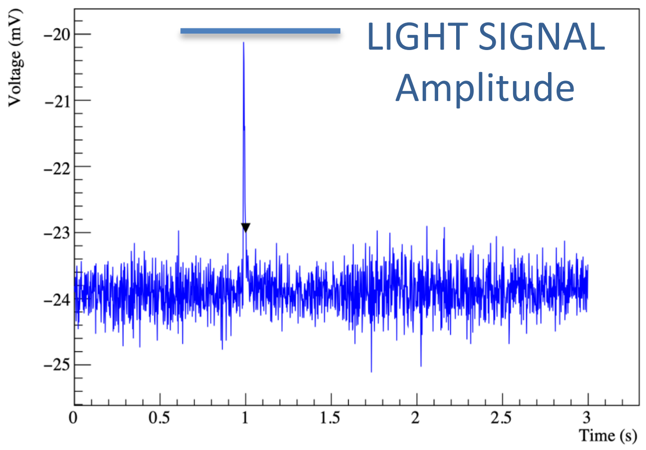
~~α background~~
~~γ background~~

No PID
$Q_{2\beta}$= 2527 keV **< 2615 keV**

PID
$Q_{2\beta}$= 3034 keV **> 2615 keV**

Coincidences between heat and light signals



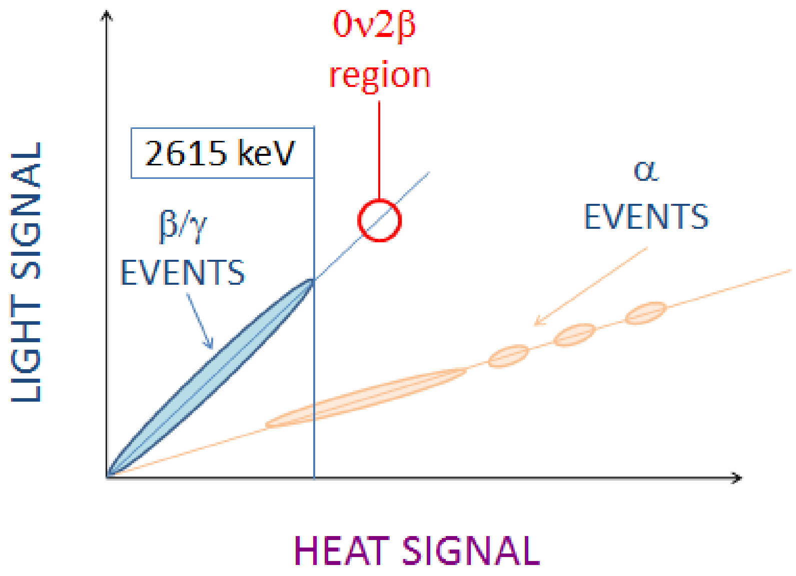


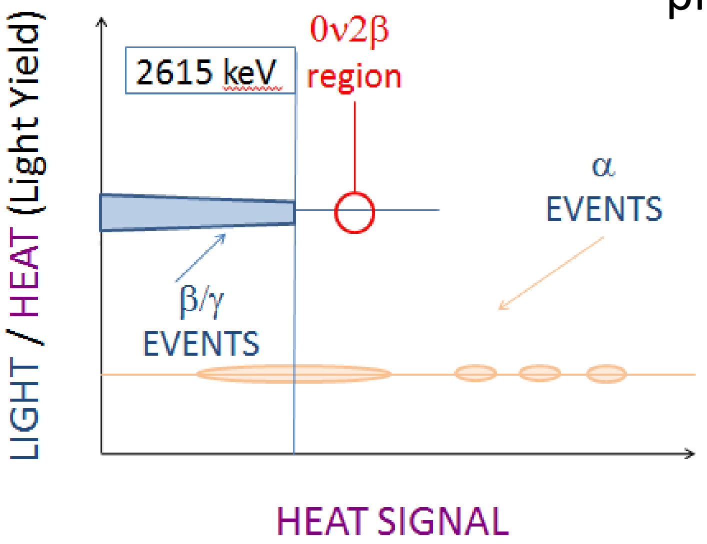
TIME [s]

Actual heat-light coincidence in the CUPID-Mo experiment

Same time scale!

Construction of heat-light scatter plot and light yield vs. heat plot

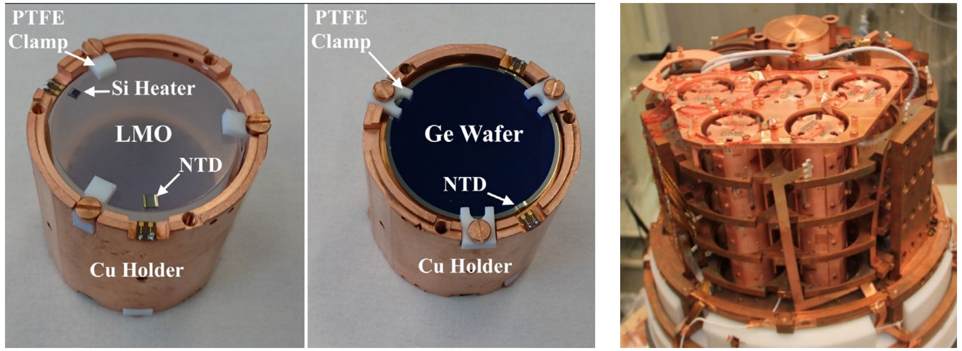




CUPID-Mo

CUPID-Mo experiment

- 20 scintillating bolometers arranged in 5 towers with Germanium light detector
- total mass of crystals is 4.16 kg corresponding to 2.26 kg of ^{100}Mo
- each scintillating bolometer consists of $Li_2{}^{100}MoO_4$ enriched (97% level)
- ~ 1.5 years of data taking
- located in the **Laboratoire Souterrain de Modane (France)** ~ 4800 m.w.e.

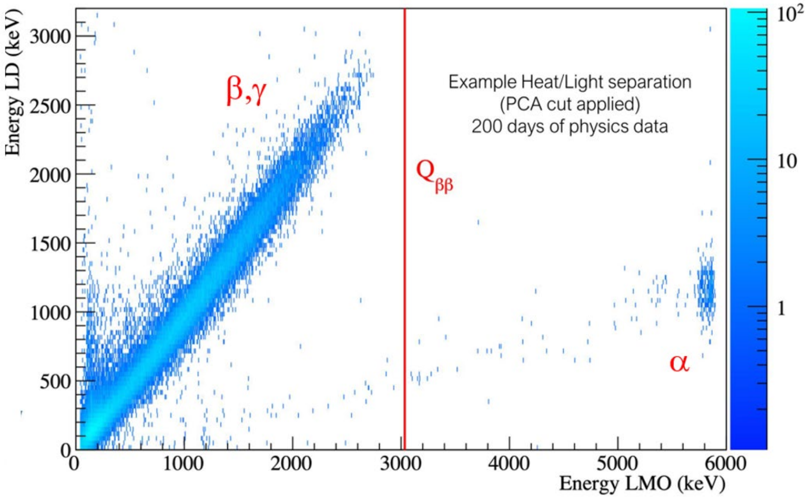


EPJ C 2023 Jul 28;83(7):675

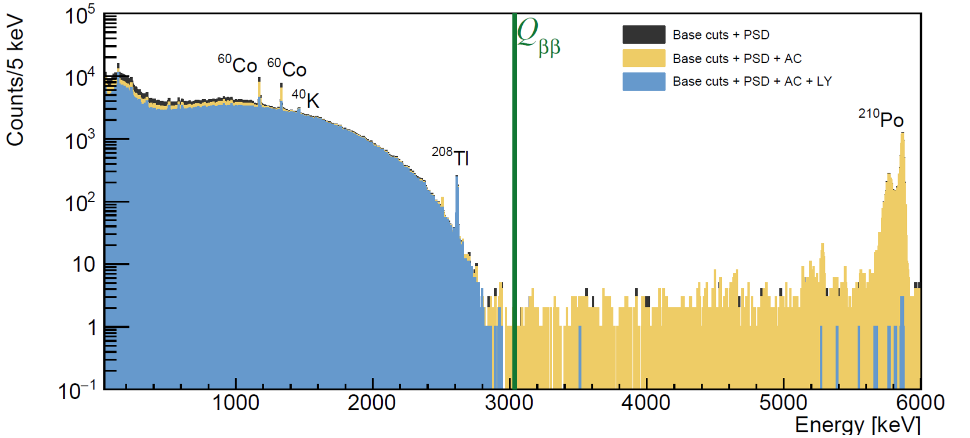
Energy resolution (FWHM)
6.6 ± 0.1 keV @ 2615 keV
7.4 ± 0.4 keV @ $Q_{\beta\beta}$ (3034 keV)

Total BI:
2.7 x 10^{-3} c/(keV kg y)

EPJ C. 2022 Nov 15;82(11):1033



99.9% α particles rejection efficiency



Final spectrum of physics data in CUPID-Mo experiment

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

$Li_2{}^{100}MoO_4$ scintillating bolometers adopted as CUPID technology

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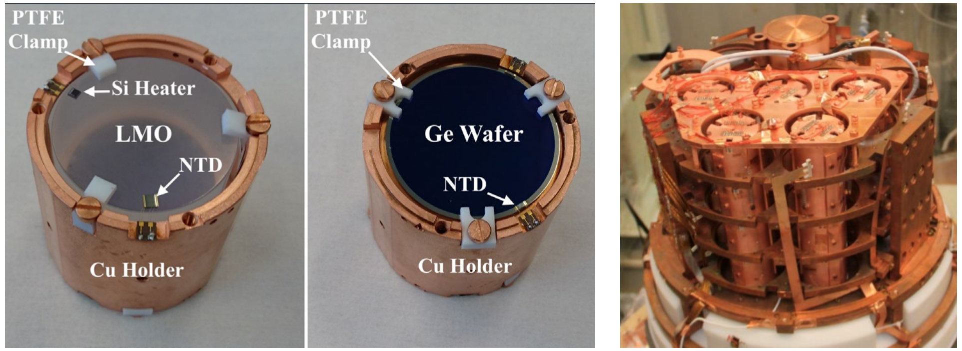

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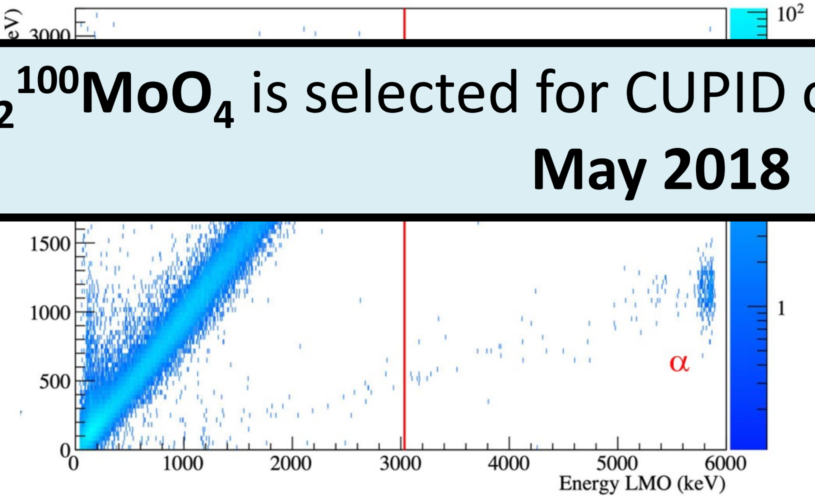
7.4 ± 0.4 keV @ $Q_{\beta\beta}$ (3034 ke

$Li_2{}^{100}MoO_4$ is selected for CUPID over $^{130}TeO_2$ or $Zn^{82}Se$
May 2018

Total BI:
2.7 x 10^{-3} c/(keV kg y)



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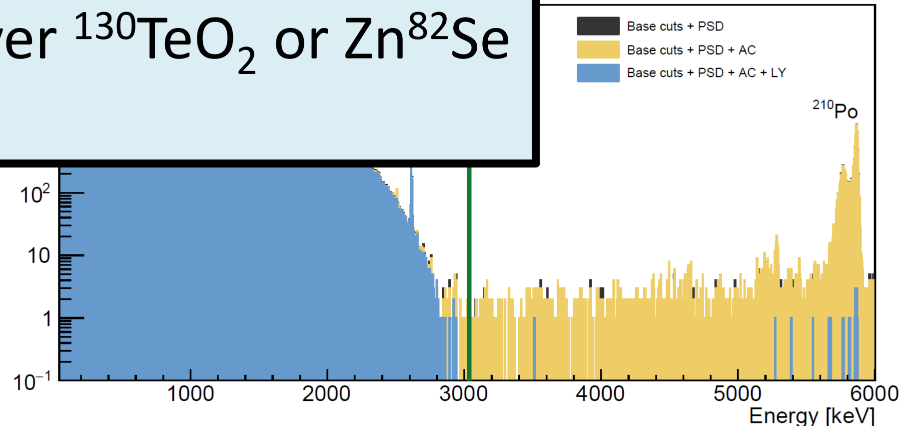

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$Li_2{}^{100}MoO_4$ scintillating bolometers adopted as CUPID technology

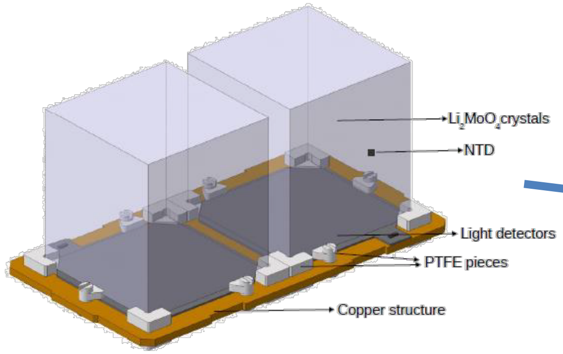
CUPID structure

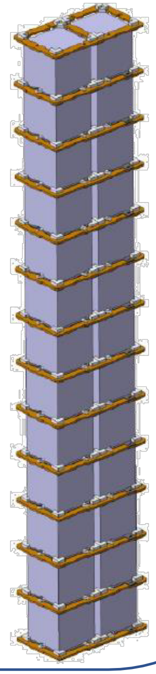
- **CUPID pre-CDR** *arXiv:1907.09376*
- **Upgraded structure** *Eur. Phys. J. C 82, 810 (2022), Eur. Phys. J. C 85, 737 (2025)*
- **TDR under finalization**

- Crystal: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g – enrichment ≥ 95%**
- Thermal sensor: **neutron transmutation doped (NTD) Ge thermistor**
- **Si heater** to stabilize the detector response
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo**
- **~1.6×10^{27}** ^{100}Mo atoms

Baseline design

Gravity stacked structure

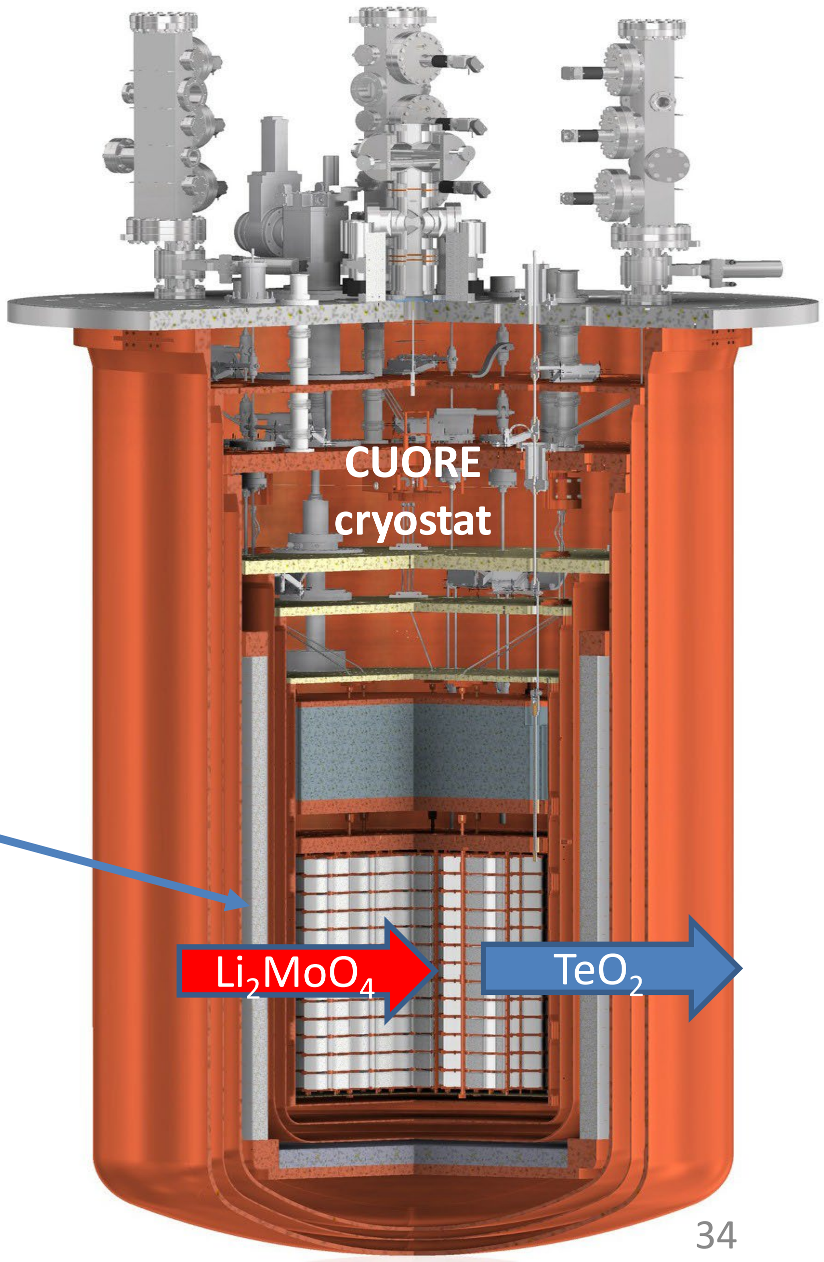




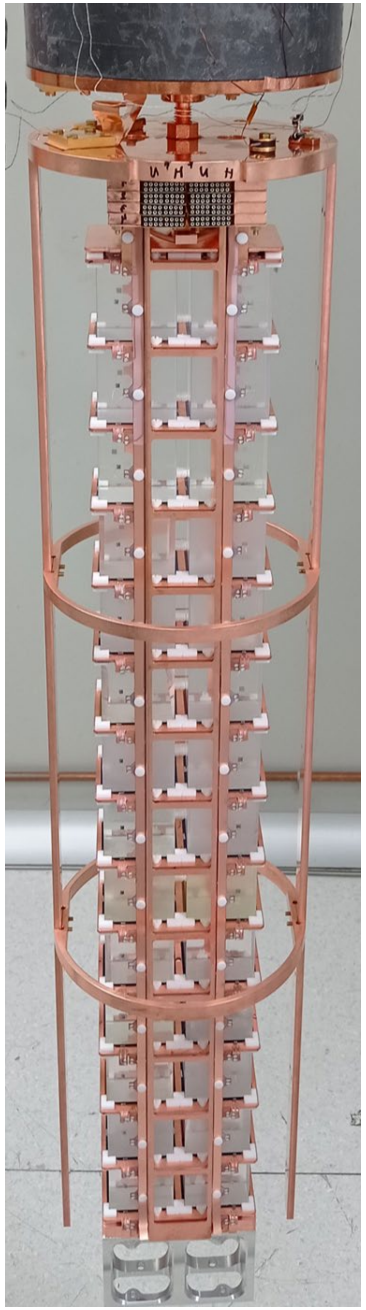
Light detectors

- Ge wafers with NTD sensor and SiO antireflective coating
- Each crystal has top and bottom LD
- No reflective foil

Muon veto for muon induced background suppression



Test of a full CUPID tower at LNGS

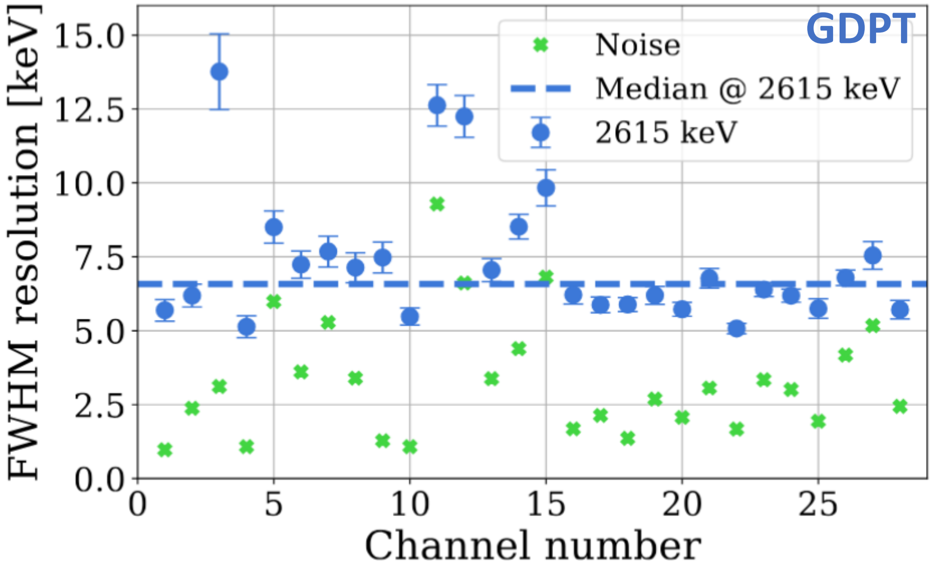


GDPT *Eur. Phys. J. C* 85, 935 (2025)
(Gravity Detector Prototype Tower)

- 28 Li_2MoO_4 crystals
- 30 Ge light detectors
- Tested at LNGS, Italy
- French contributions: gluing at IJCLab, participation in on site assembly

Results:

- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance: median $FWHM_{2615\ keV}$ = 6.2 keV
- Median light yield: 0.36 keV/MeV
- Some excess noise on the LD -> changes to the LD assembly structure for the next test

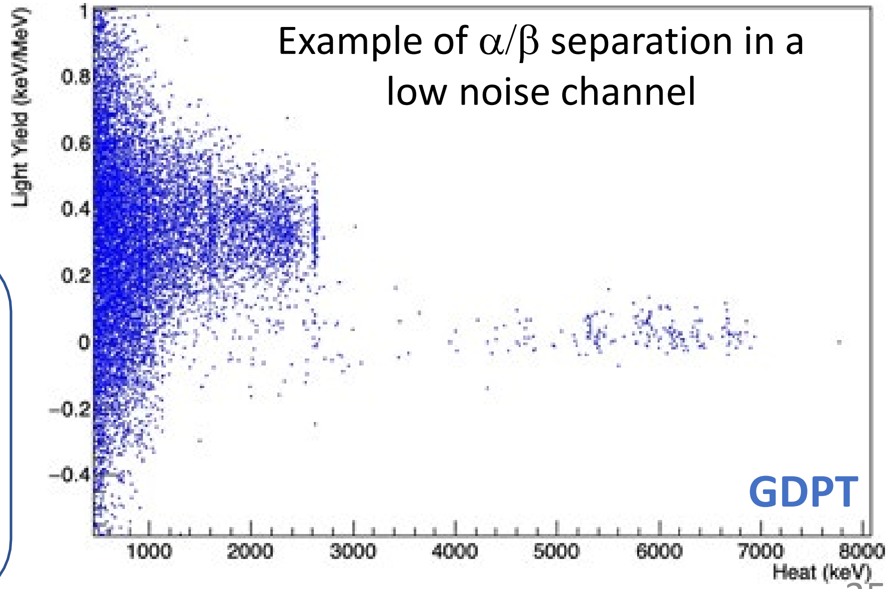


Current test: VSTT (Vertical Slice Test Tower)

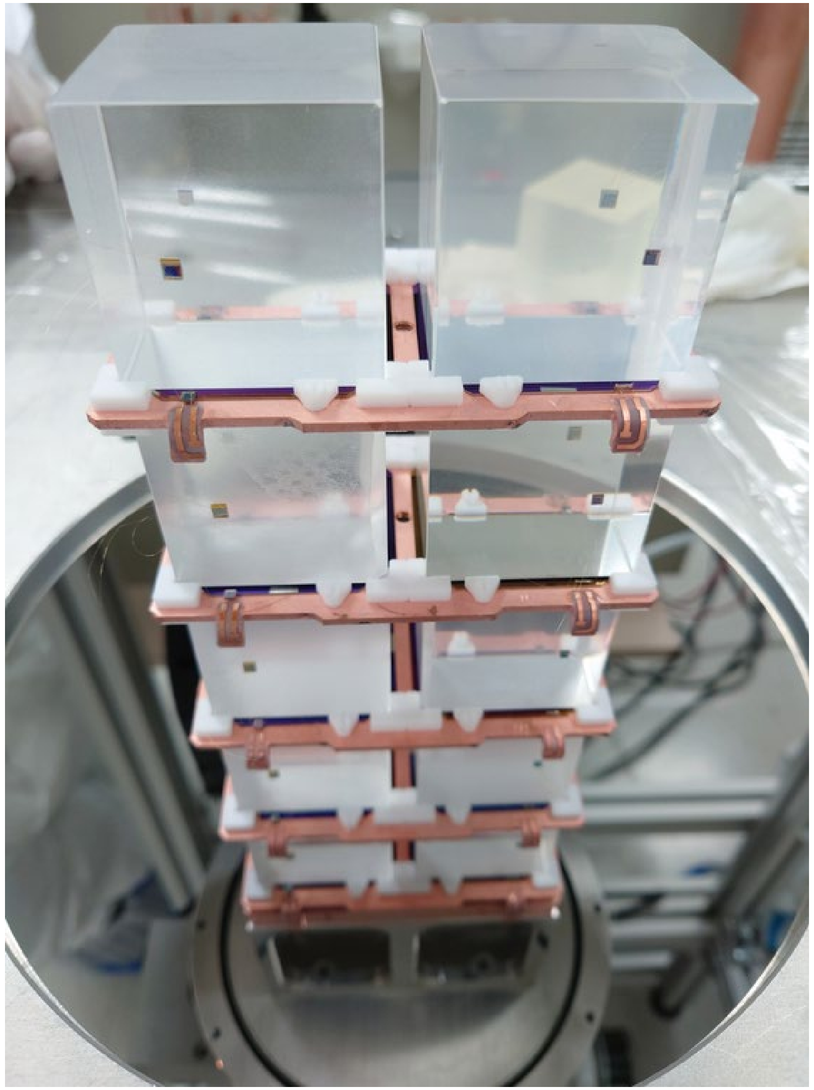
- Under operation in LNGS now

What's new?

- Enhanced light detectors (NTL amplification)
- Changes to the LD holding system to mitigate the noise
- Full test of the assembly line




TODDLER



Status of crystal procurement

FWHM ~ 5-7 keV - **LY ~ 0.3 keV/MeV** - **internal radioactivity (U, Th) ≤ 0.5 μBq/kg**

- Outstanding **performance** and **radiopurity** obtained with **Russian crystals**:
  Enrichment (**Rosatom**) + **Crystallization** (**NIIC, Novosibirsk**) → **CUPID-Mo**, **CROSS**
- Because of the invasion of Ukraine the procurement of enriched crystals from Russia is now **impossible**

Chinese baseline: IPCE (subsidiary of CNNC) for **enrichment** + **SICCAS** (Shanghai) for **crystals**

IPCE: it has already produced several kg of ^{100}Mo in 2024 for CUPID/CROSS
Active in medical production

SICCAS: extremely reliable company with excellent tracking record in large scale experiments:

- ~1000 TeO_2 crystals in CUORE
- ~4000 $PbWO_4$ crystals for CMS, Jlab Hybrid EmCal, PANDA EMCal, NPS project

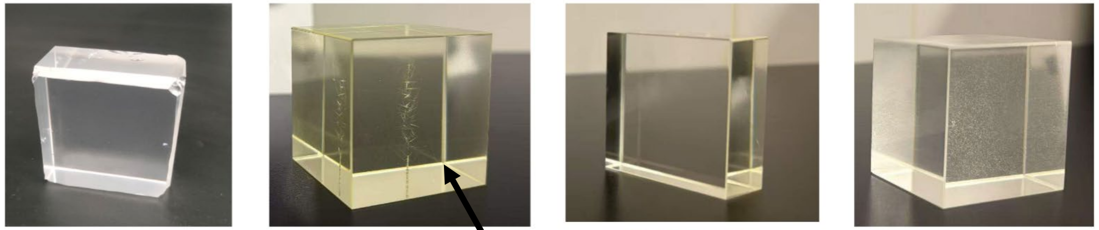
French alternative:

- Crystallization technique from ANR CLYMENE at SIMaP/INP Grenoble
- Companies LUXIUM (Gières, Grenoble) for crystals and ORANO (Tricastin) for ^{100}Mo enrichment

Status of crystal procurement

IPCE + SICCAS: production and experimental tests

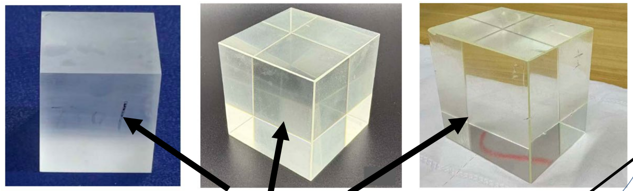
- Pre-production – French + Italian contracts
- **Seven** enriched crystals **produced** so far (**Bridgman method**)



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

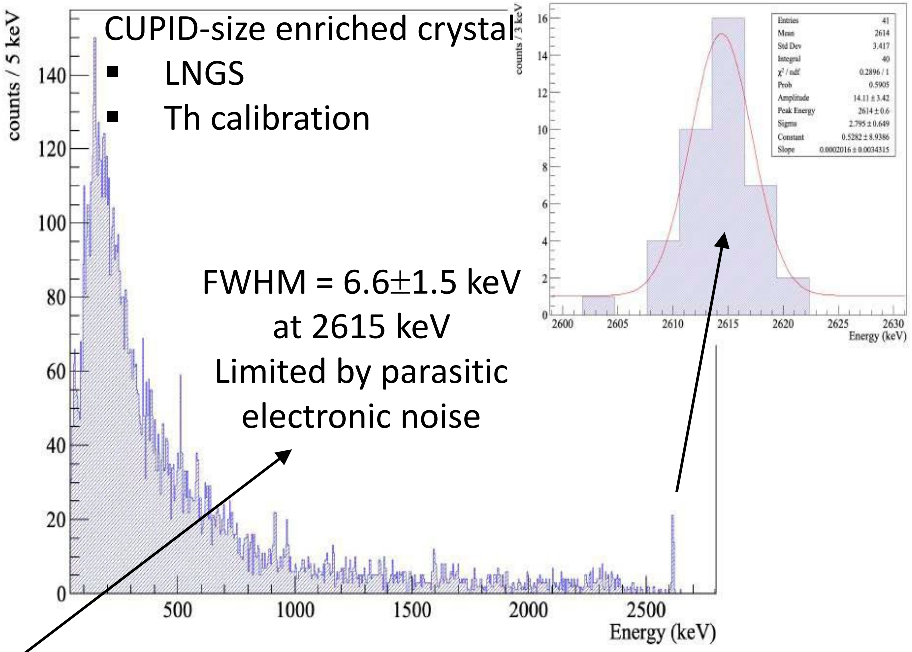
Nominal CUPID size

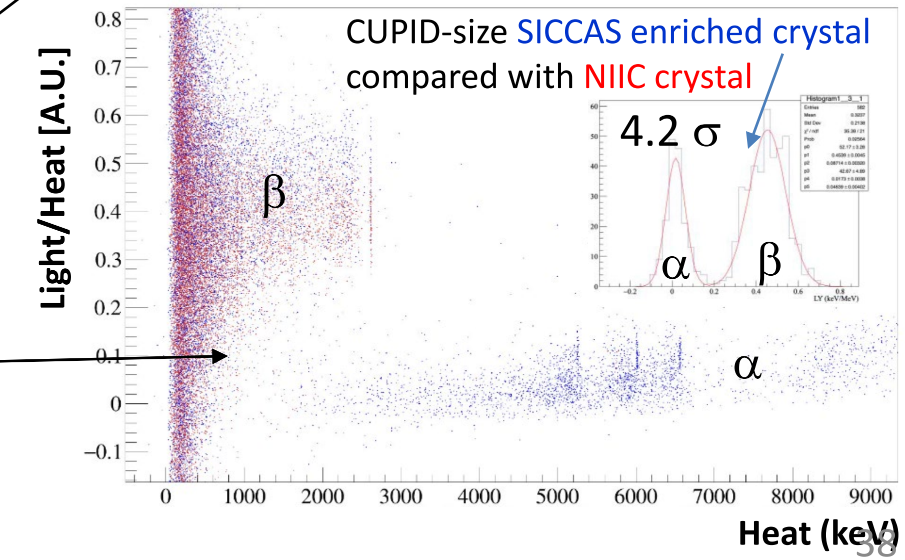
- **Four** crystals have been **tested** in IJCLab, LNGS and CEA/IRFU
- **Three** additional CUPID-size crystals will be tested at LNGS soon



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





Status of crystal procurement

- **Radiopurity was not a priority so far** → Optimization of crystallization process and test of bolometric performance

Now the radiopurity phase has started

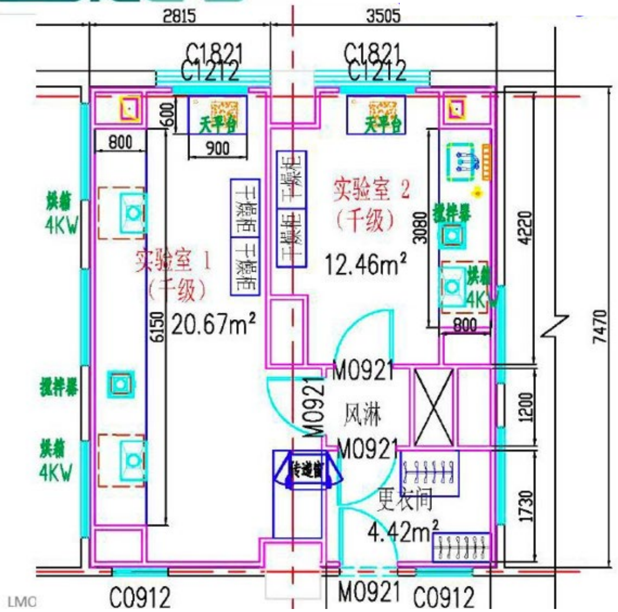
- IPCE and SICCAS are working together to produce **ultra-pure Li_2MoO_4 powder** ready to be placed in crucible
- Big furnaces for mass production will be fabricated with **low radioactivity materials**
- **Reduction of dust** in the furnace area
- Develop a **dedicated clean room** for **crystal processing** (cutting, grinding, polishing and packaging)
- Selection of **grinding and polishing material**

Objective

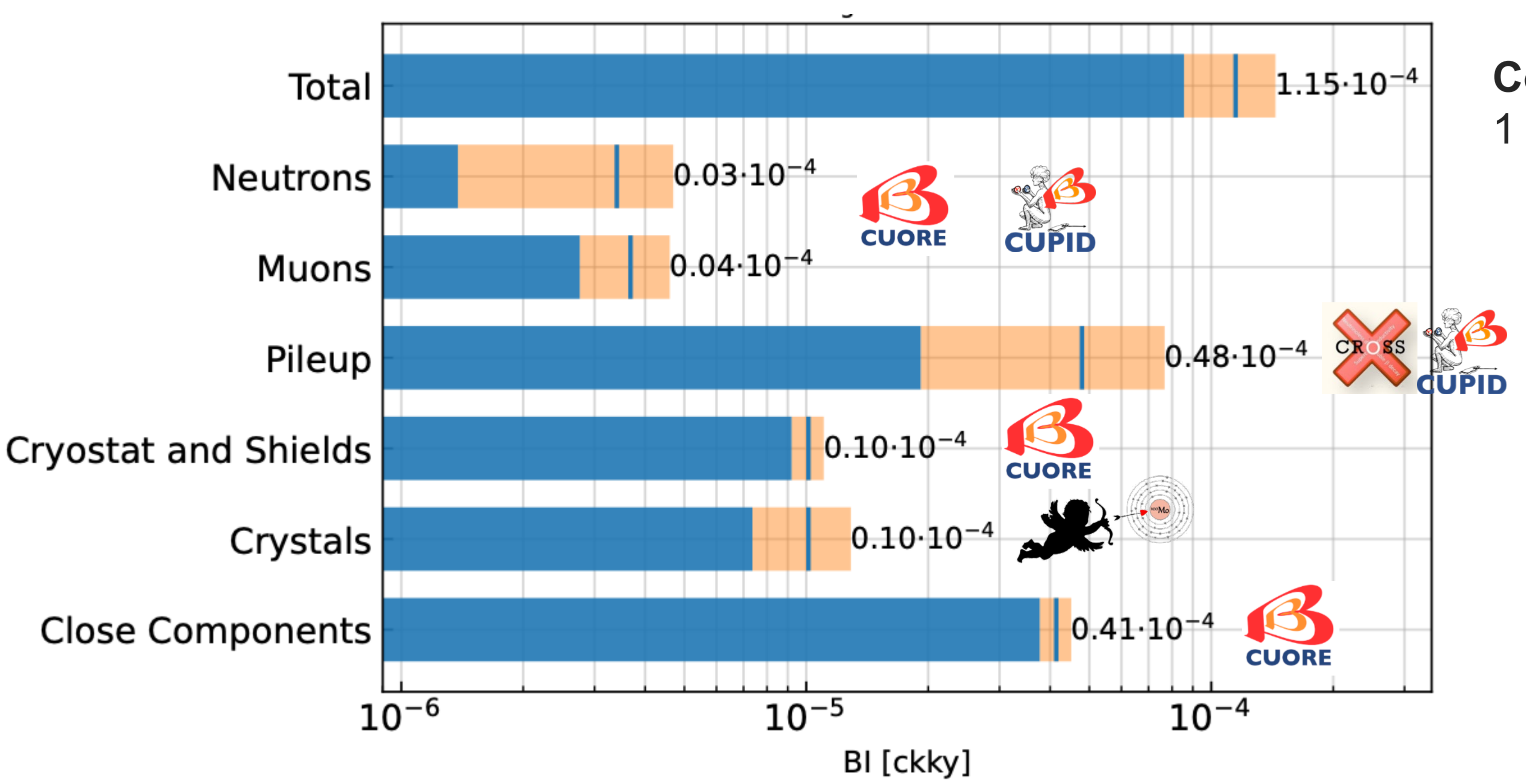
Purchase contract in **mid 2026** for **CUPID-Stage-I**

SICCAS Since 1928

Clean room for processing



CUPID background budget



Conservative prediction
1 σ range: [0.86, 1.44] 10^{-4} counts/keV/kg/yr

Phys. Rev. D 110 (2024) 052003

Data driven: based on CUORE and CUPID-Mo background models

Eur. Phys. J. C 83 (2023) 675

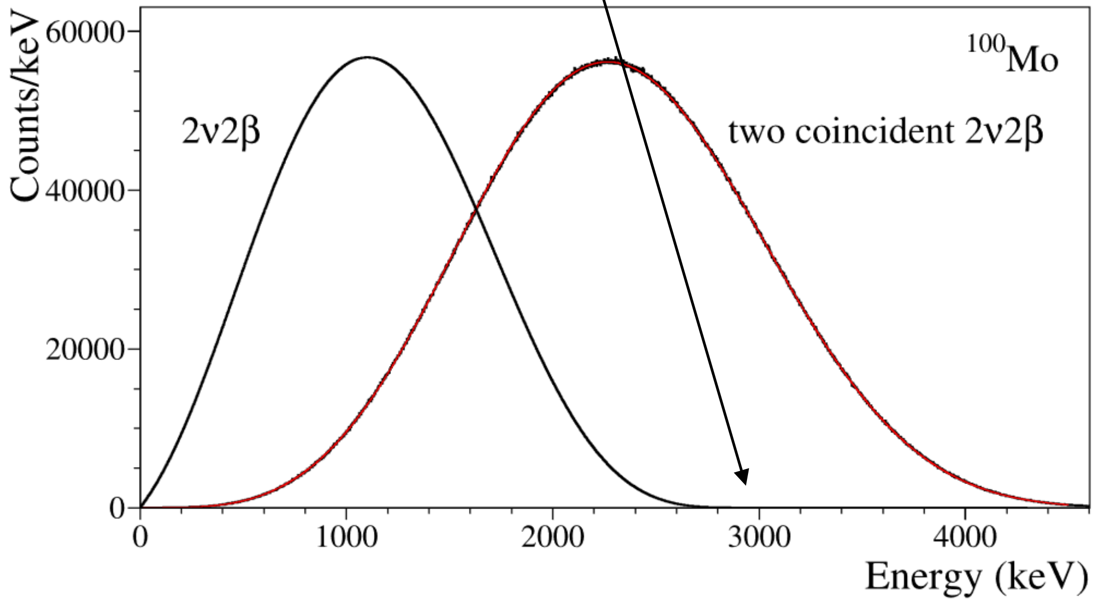
- CUPID's background projections are robust
- In-situ characterization and conservative assumptions
- 10^{-4} counts/keV/kg/yr as project target or better are in reach

Pile up of ordinary 2ν2β events

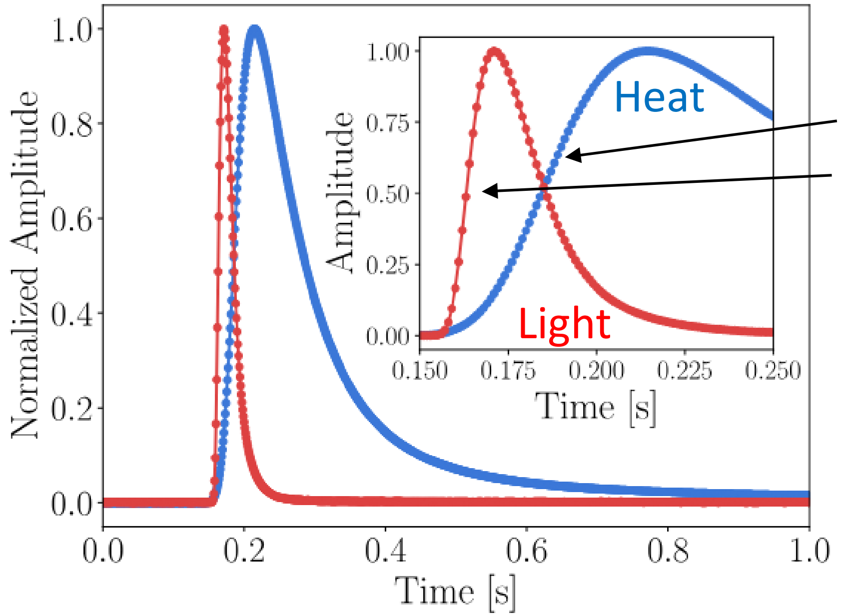
- **Fast 2ν2β transition in ^{100}Mo**: $T^{2\nu}_{1/2}$ = **7×10^{18} y** → 2ν2β activity in a CUPID crystal: **~2.6 mBq**
- Significant pile-up probability due to a **random coincidence of 2ν2β events** → background in the region of interest
- **$b_{2\nu2\beta}$ = (δT / 1 ms) · 3.3 x 10^{-4} counts/(keV·kg·y)** → **δT ~ 0.17 ms** is required to meet the CUPID 2ν2β background goal

pulse pair resolving time

0.5 x 10^{-4} counts/(keV·kg·y)



Heat-light coincidence



Rise-time ~ 15 ms

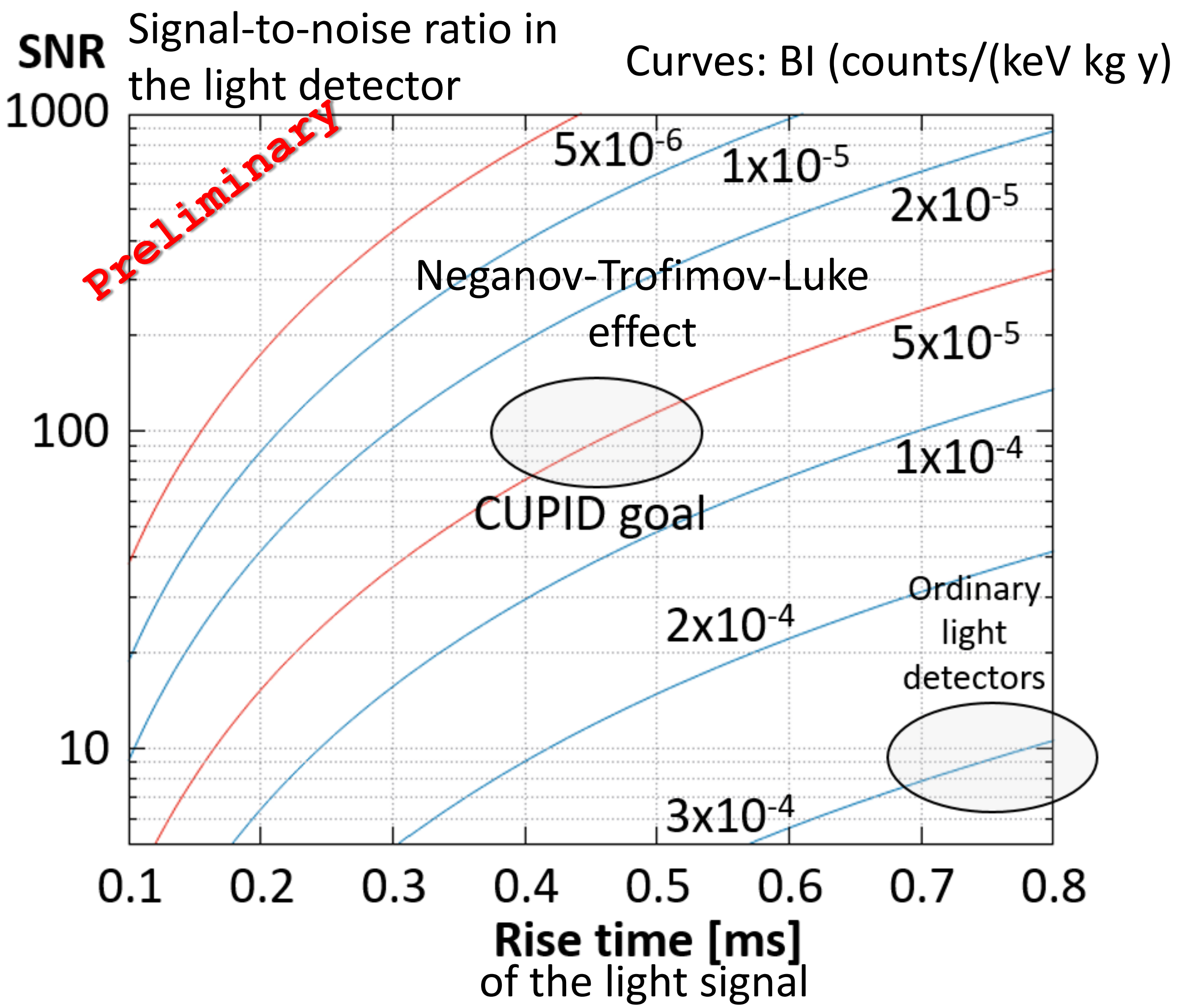
Rise-time ~ 1 ms

Use light detector for pile-up discrimination

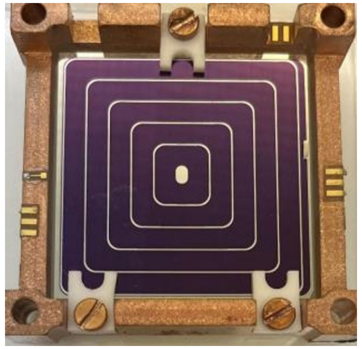
But SNR ~ 10 only

Pile-up and light detector role

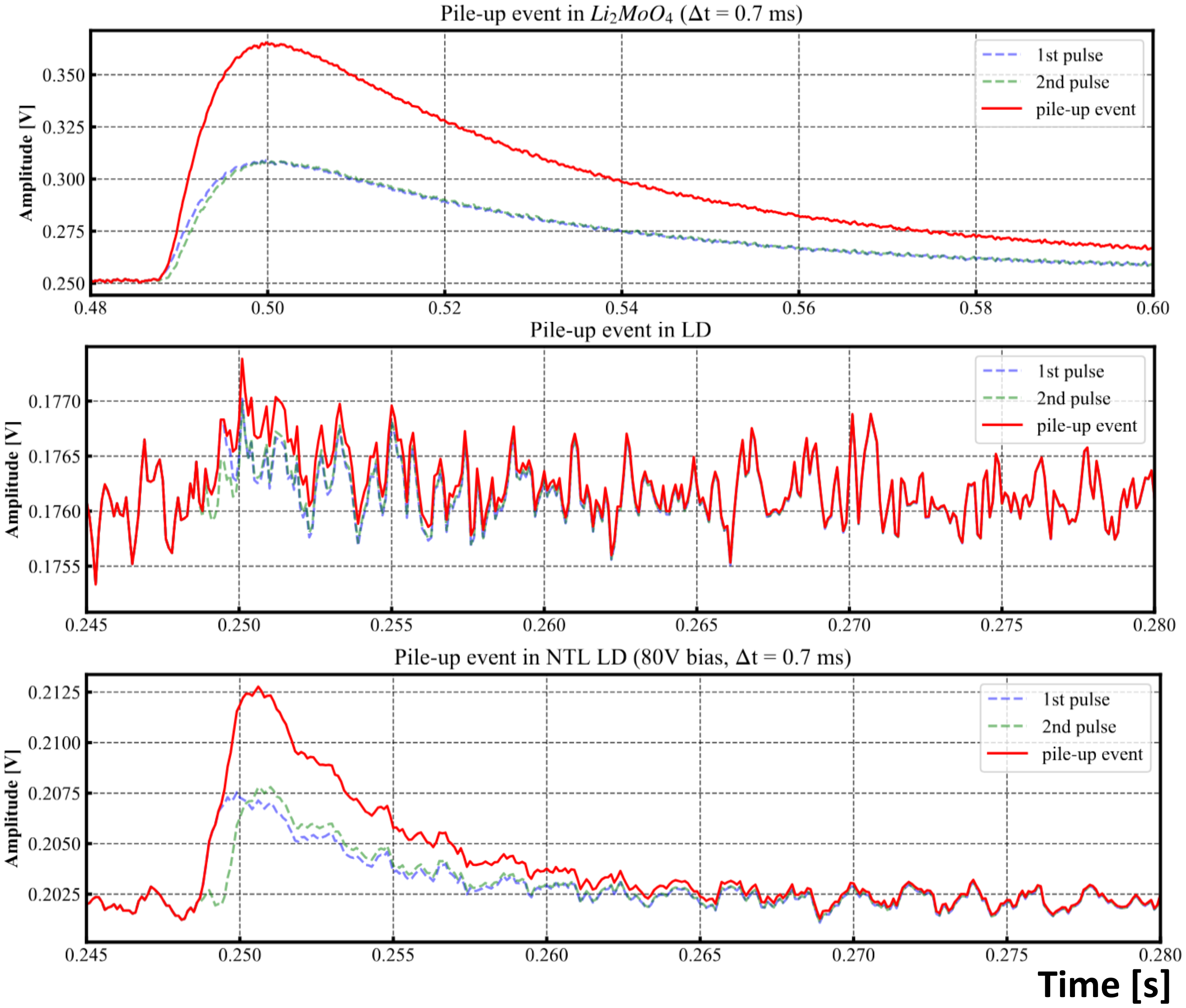
- **Light detectors** are essential to reject the pile-up at the desired level
- Ordinary light detectors are not enough: they must be enhanced by the **Neganov-Trofimov-Luke effect (NTL)**



- Establish an **electric field** in the light detector wafer via a set of Al electrodes
- Electron-hole pairs created by light absorption drift in the field and produce **additional heat**
- An **amplification of the thermal signal** by a factor 10-20 is technically possible
- **SNR is increased by an order of magnitude**



How NTL helps rejection of pile-up



Pile-up event as seen by the **heat channel**
Summed amplitude → $0\nu2\beta$ signal
ΔT=0.7 ms
Rise-time ~ 10 ms

Same event seen by the **light channel**
No Neganov-Trofimov-Luke effect
Rise-time ~ 0.5 ms

Same event seen by the **light channel**
Neganov-Trofimov-Luke effect with ΔV=80 V
Pulse shape discrimination is possible

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)**

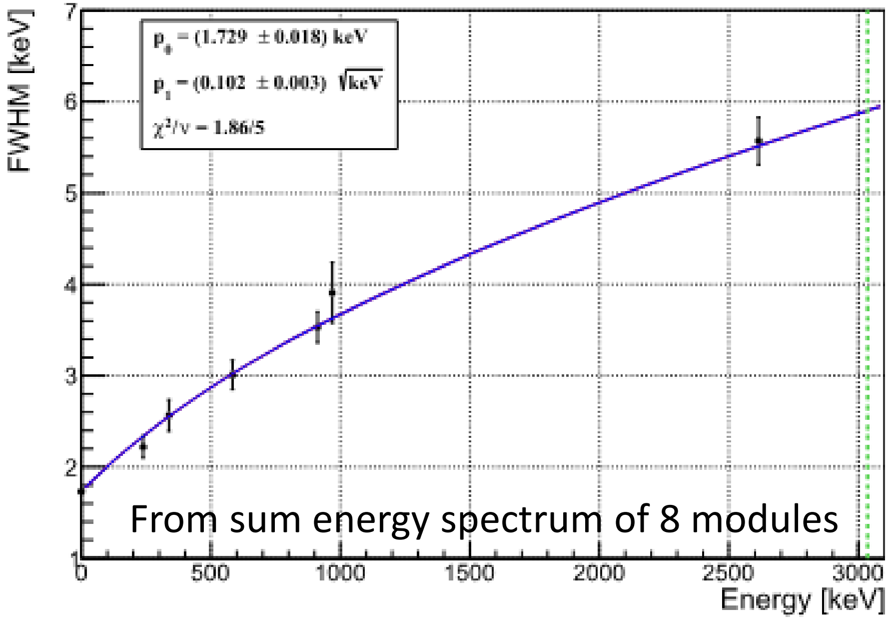
demonstrated in tens of large mass scintillating bolometers based on enriched Li_2MoO_4 crystals

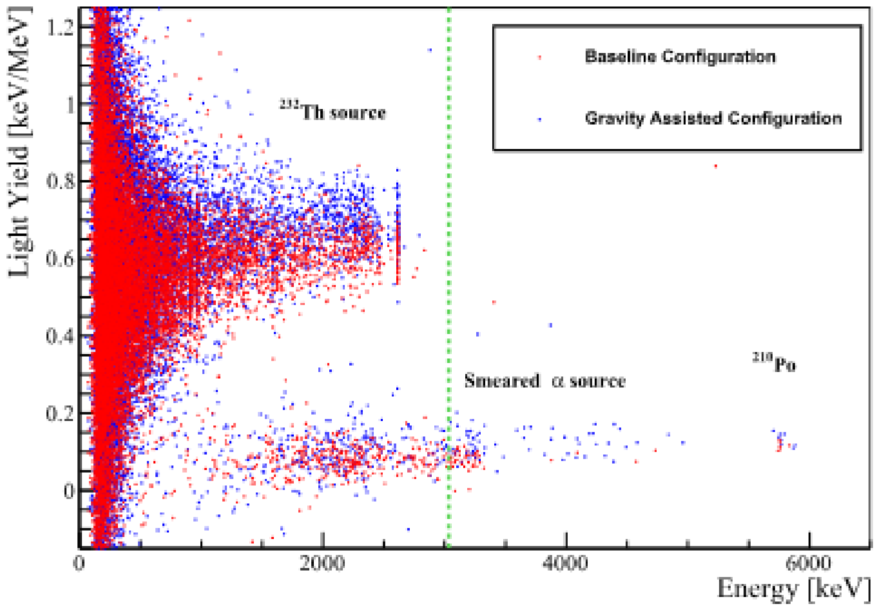
CUPID-Mo, GDPT, CUPID and CROSS prototypes

- **Enhanced-sensitivity light detectors** bring the $2\nu2\beta$-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)



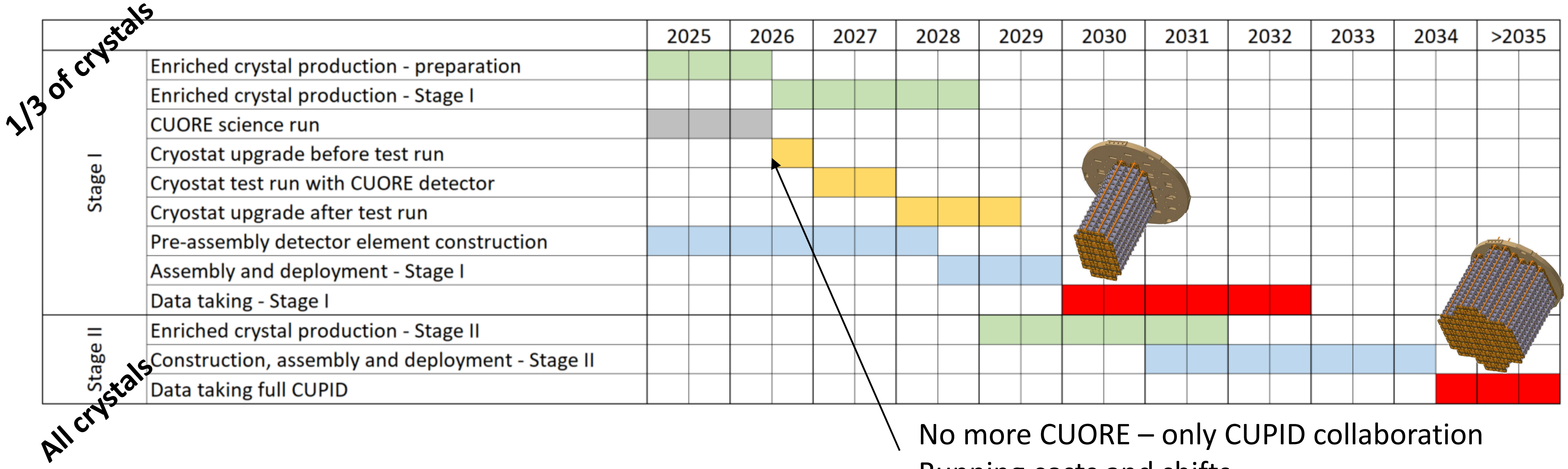


CUPID timeline

The collaboration decided to move to a **staged deployment** for CUPID implementation

Three key advantages

1. **Data taking starting in 2030** while the remaining crystals are still being produced $\rightarrow$ **early leading role in $0\nu2\beta$ search**
2. **Preservation of critical expertise** in running detectors and cryogenics **during the CUORE-to-CUPID transition**
3. **Room for optimization, improvement, and risk mitigation**.



No more CUORE – only CUPID collaboration
Running costs and shifts

CUPID sensitivity

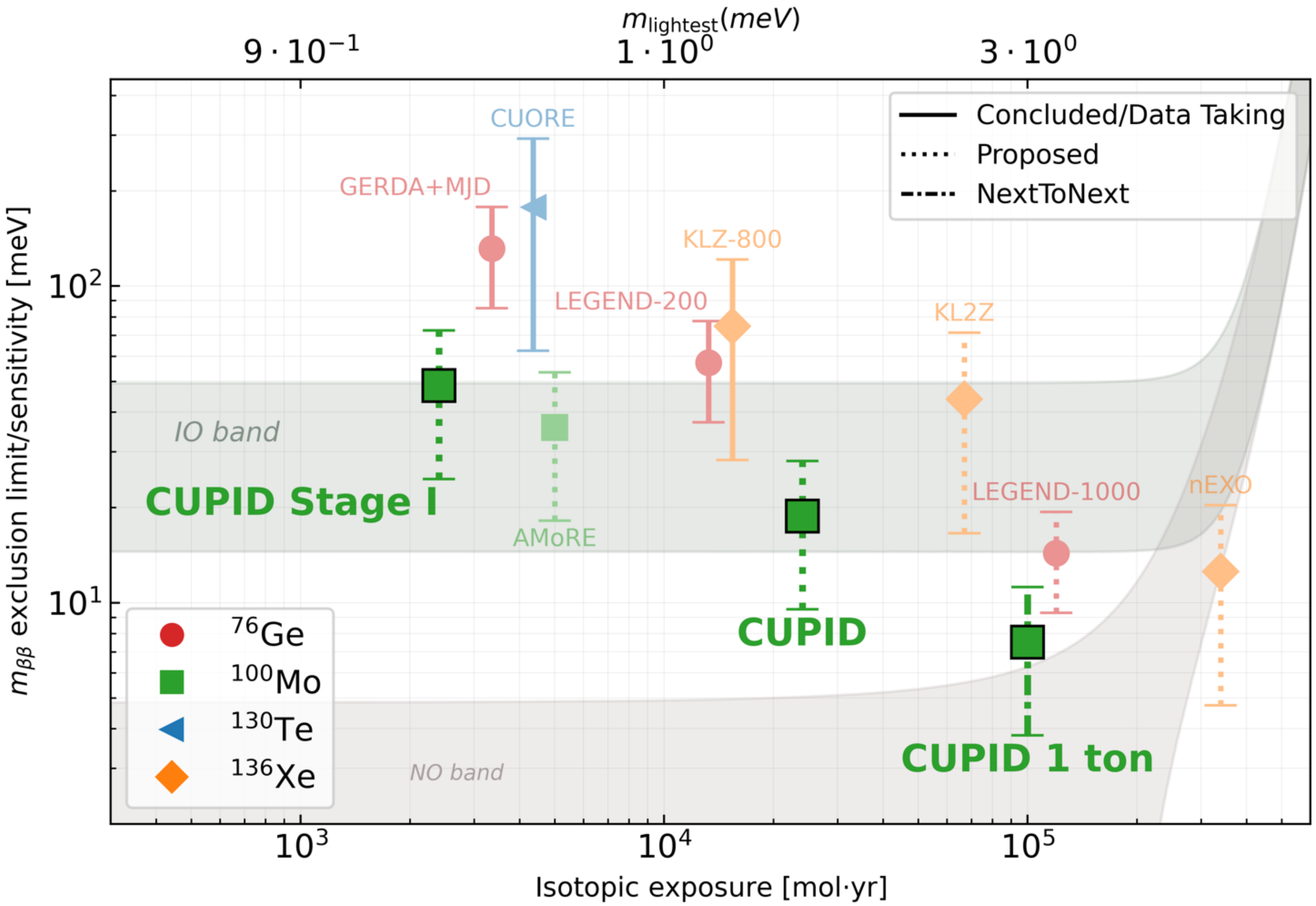
- **Exclusion sensitivity 90% C.I.** (10 yrs livetime - 240 kg ^{100}Mo + 5 keV FWHM)
  $T^{0\nu}_{1/2}$ > 1.4 x 10^{27} yr **$m_{\beta\beta}$ < (9.5-28) meV**

- **3 σ - discovery sensitivity**
  $T^{0\nu}_{1/2}$ > 1 x 10^{27} yr **$m_{\beta\beta}$ < (12-35) meV**

- **BI < 1 x 10^{-4} count/(keV kg y)** i.e. **100 less than in CUORE**
  ÷ 10 thanks to α particle rejection (dominating CUORE background)
  ÷ 10 thanks to high $Q_{\beta\beta}$ that brings 0νββ signal far from the γ dominated region

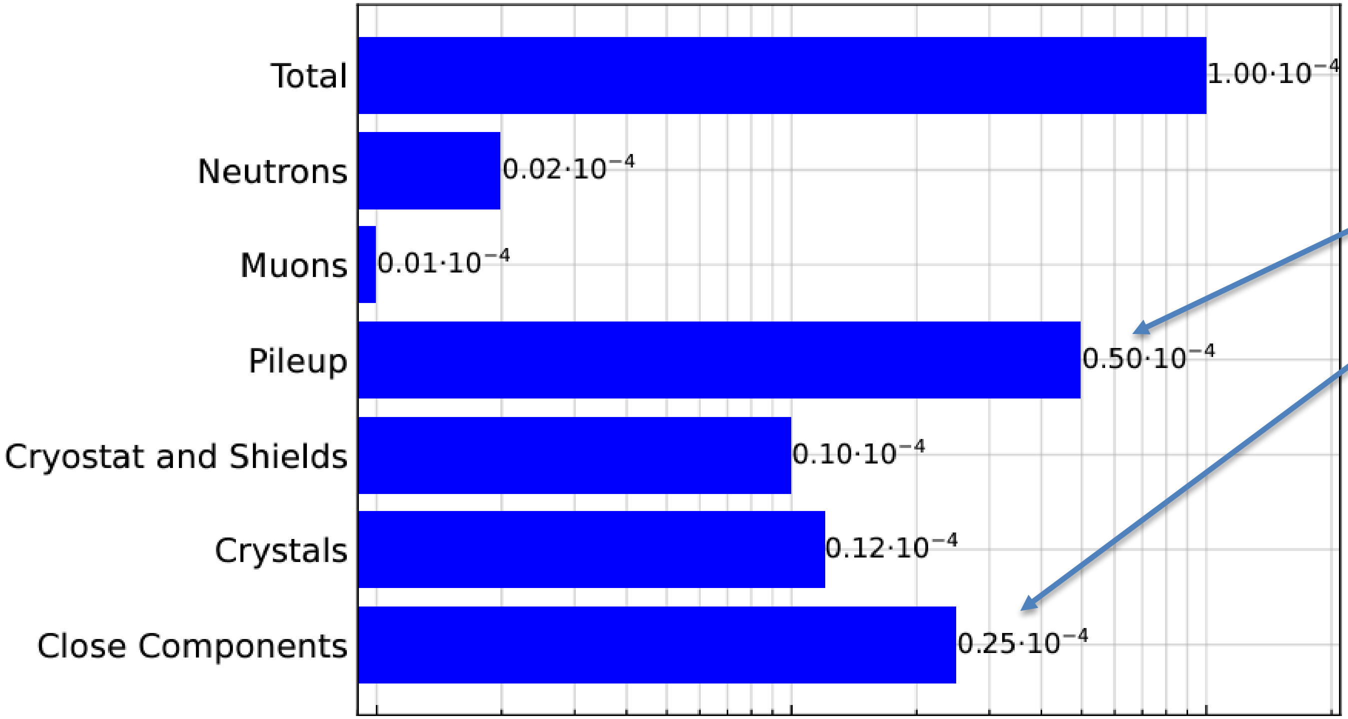
- **Projections** **based on current available data** **BI = 1.1 x 10^{-4} ckky**
  our BI is conservative, we have room for further improvements !!!

CUPID competitiveness



Is CUPID-1T feasible?

- **1 ton of ^{100}Mo** – 228 CUPID-like towers – 6400 Li_2MoO_4 enriched crystals → **4x CUPID**
- Cryogenic is possible: very large pulse-tube dilution refrigerators are built for quantum computing
- Target for the background index: **BI = 5x10^{-6} c/(keV kg y)** → **(1/20) x CUPID** (0.45 count/10y expected in FWHM)



These two components must be reduced by more than one order of magnitude

Pile-up: further increase in SNR and speed of light detectors

Close components: β surface radioactivity:

- Successful implementation of CROSS surface sensitivity
- New approach: BINGO assembly technique

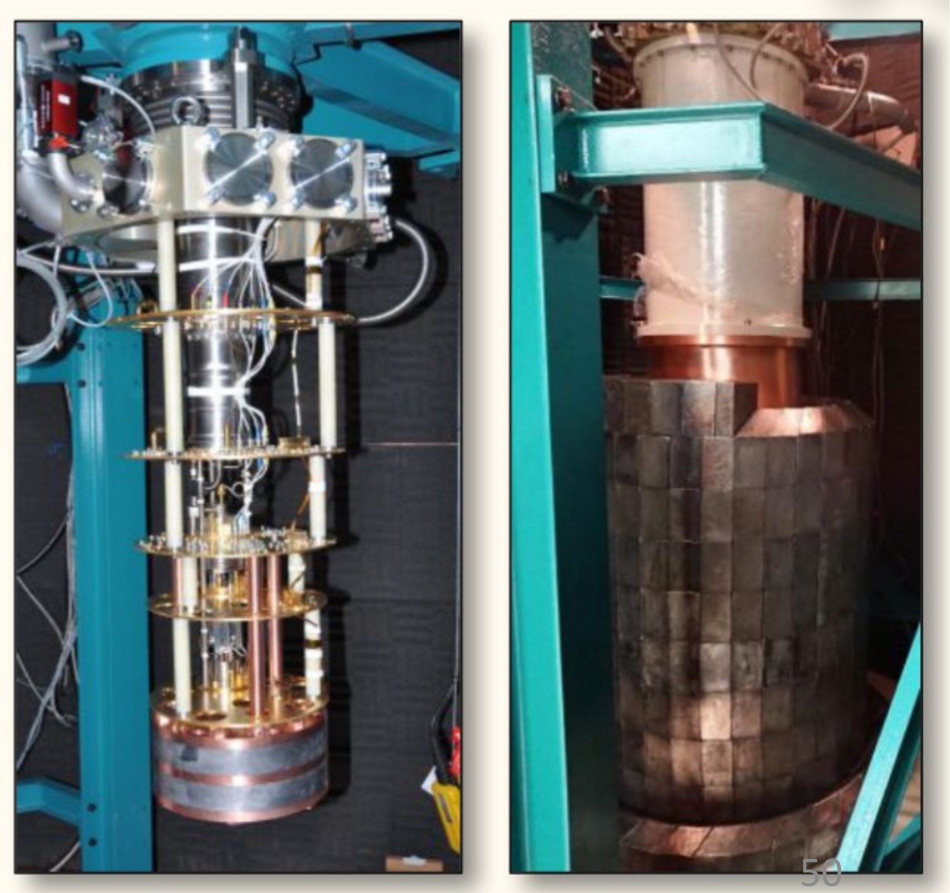
CROSS

CROSS project

A standalone experiment and a test bench for CUPID

The CROSS experiment aims to develop new strategies to reduce the background contribution with origin in the surface of the detectors and the surrounding materials

Underground cryogenic facility at LSC (Spain)
Lead shielding, anti-radon shield and muon veto



Two high Q-value 2β isotopes studied:

- ^{100}Mo: Q-value = 3034 keV (as in CUPID-Mo and CUPID)
- ^{130}Te: Q-value = 2527 keV (as in CUORE)

Measures heat and light channels by using NTL light detectors
Bolometers are made of crystals enriched with the 2β isotopes

New technologies:

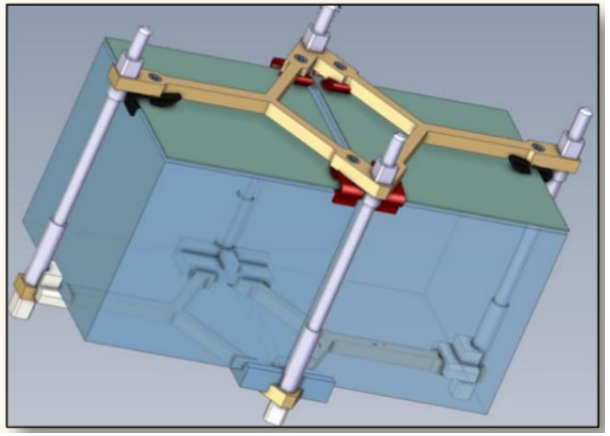
- **Surface film coating** of crystals to discriminate between bulk and α/β surface events
- **Neganov-Trofimov-Luke (NTL) Light Detectors** development and optimization

CROSS demonstrator: structure

3 towers with 7 floors each

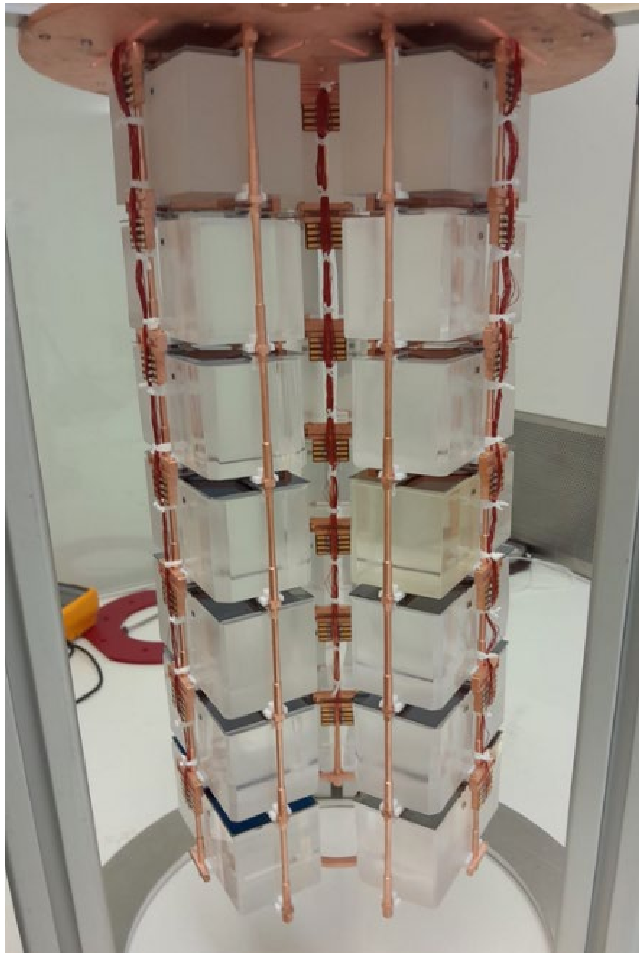
Test of different light detectors in each tower:

- Ge wafers with circular electrodes
- Ge wafers with square electrodes
- Si wafers with spiral electrodes



M. Buchynska, WIN 2025

2024 *JINST* 19 P09014



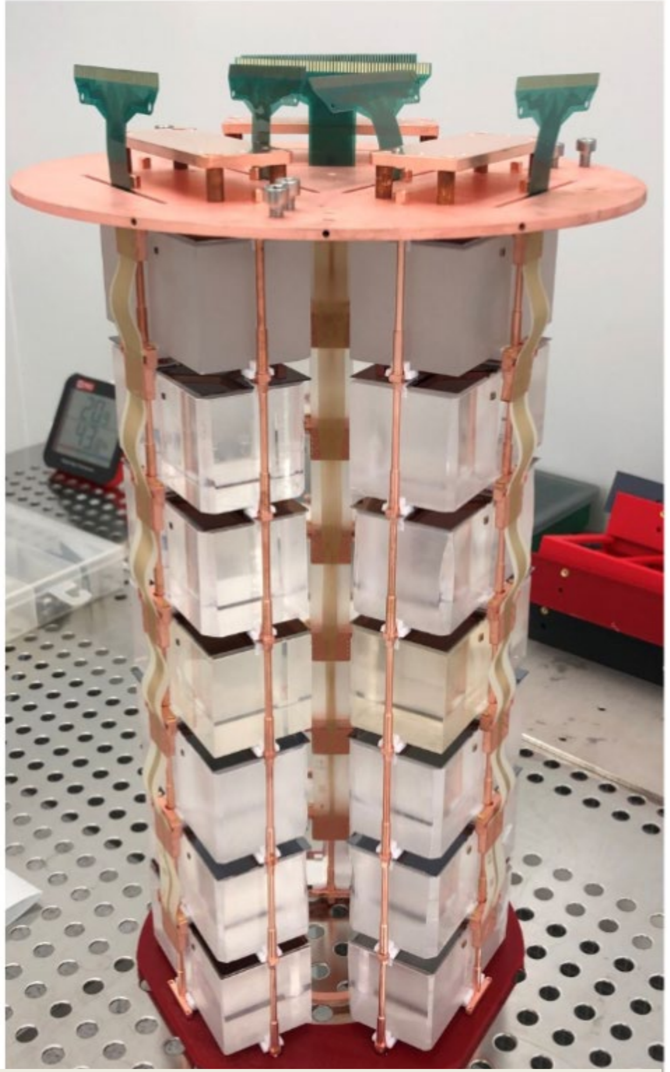
In total: 36x Li_2MoO_4 (6 natural, 32 enriched) and 6x $^{130}TeO_2$

- **Total mass of ^{100}Mo: 4.7 kg**
- **Total mass of ^{130}Te: 2.6 kg**

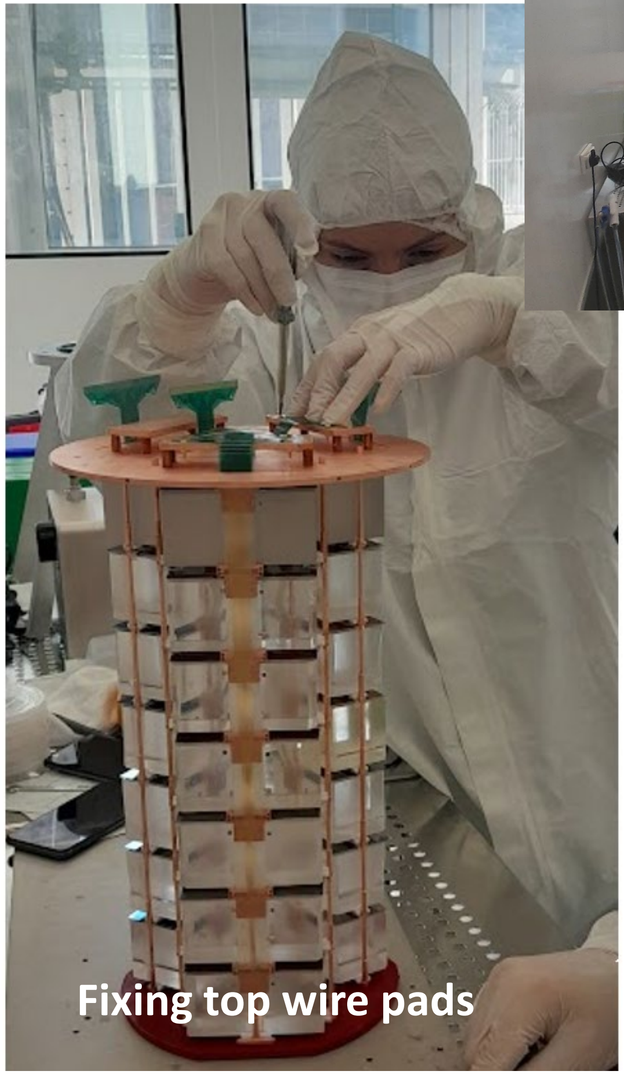
Detectors now installed in the Canfranc underground laboratory

- **Commissioning in September 2025**
- **Data taking to be started in October 2025**

CROSS demonstrator: assembly

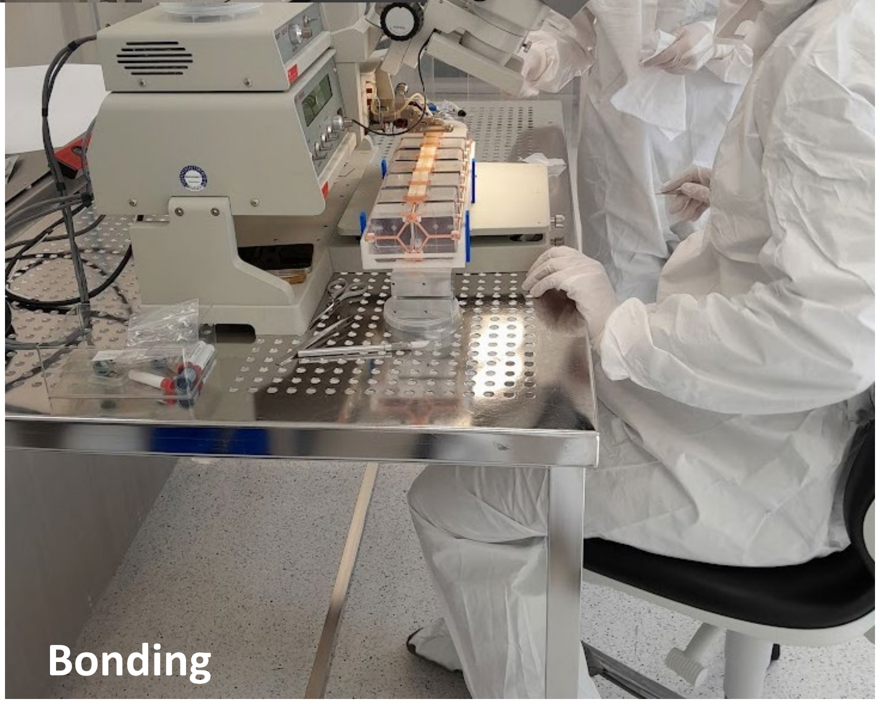


Assembled demonstrator
(baseline version of the cabling)



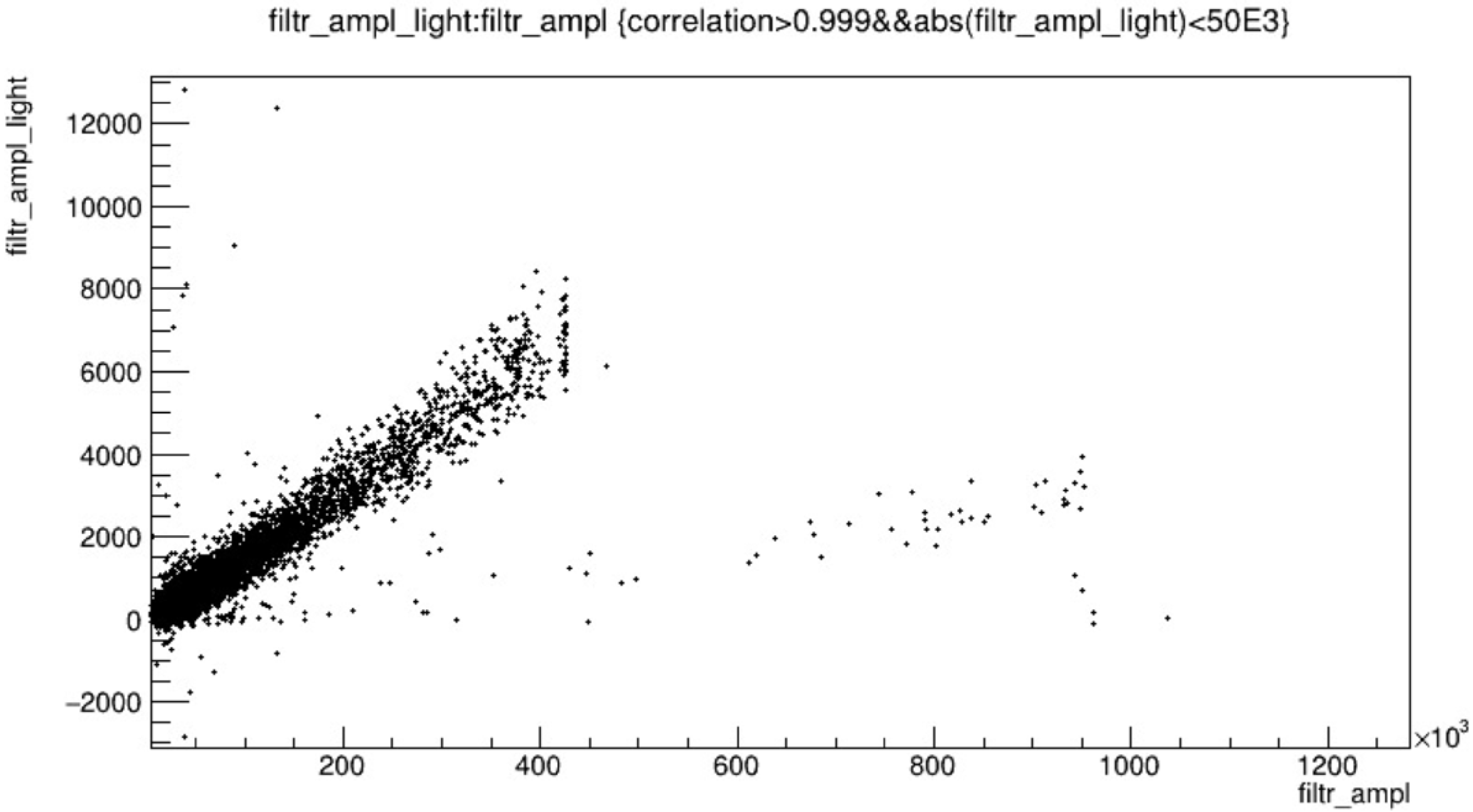
Fixing top wire pads

IJCLab-Orsay
ISO5 clean room

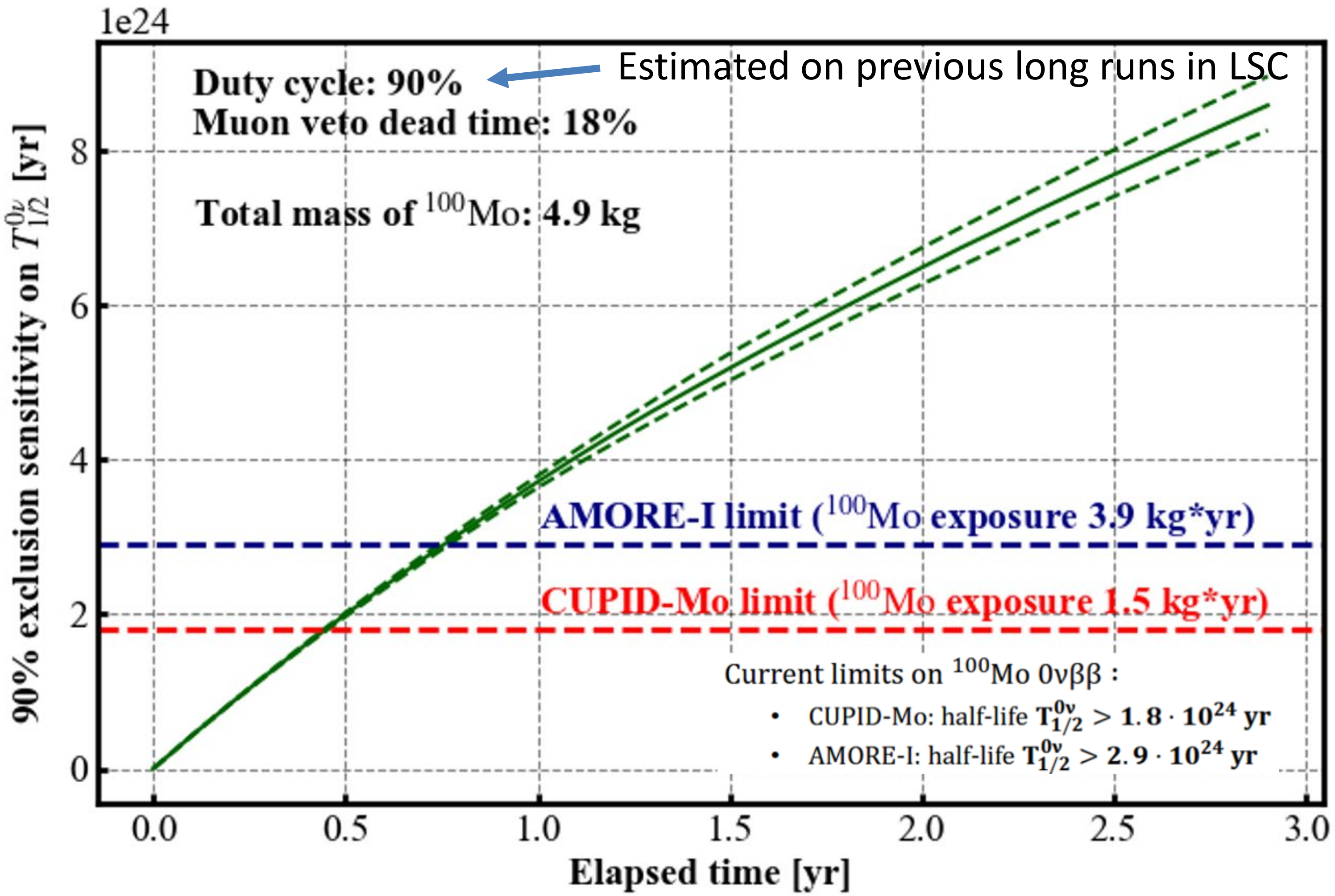


Bonding

First scatter plot! (yesterday…)



Sensitivity



Assumptions:

Resolution: **7 keV FWHM @ Qββ**

ROI: 17.1 keV
(from CUPID-Mo analysis)
BI: (3.2±0.5)x10^{-3} counts/(keV kg y)

Number of ^{100}Mo nuclei: 2.95x10^{25}

Efficiency 70.2%
- Containment efficiency: 78%
- Cut efficiency 90%

We expect to reach a sensitivity on ^{100}Mo $T^{0\nu}_{1/2}$ of **3.5x10^{24} y before the end of 2026**

Summary and final considerations

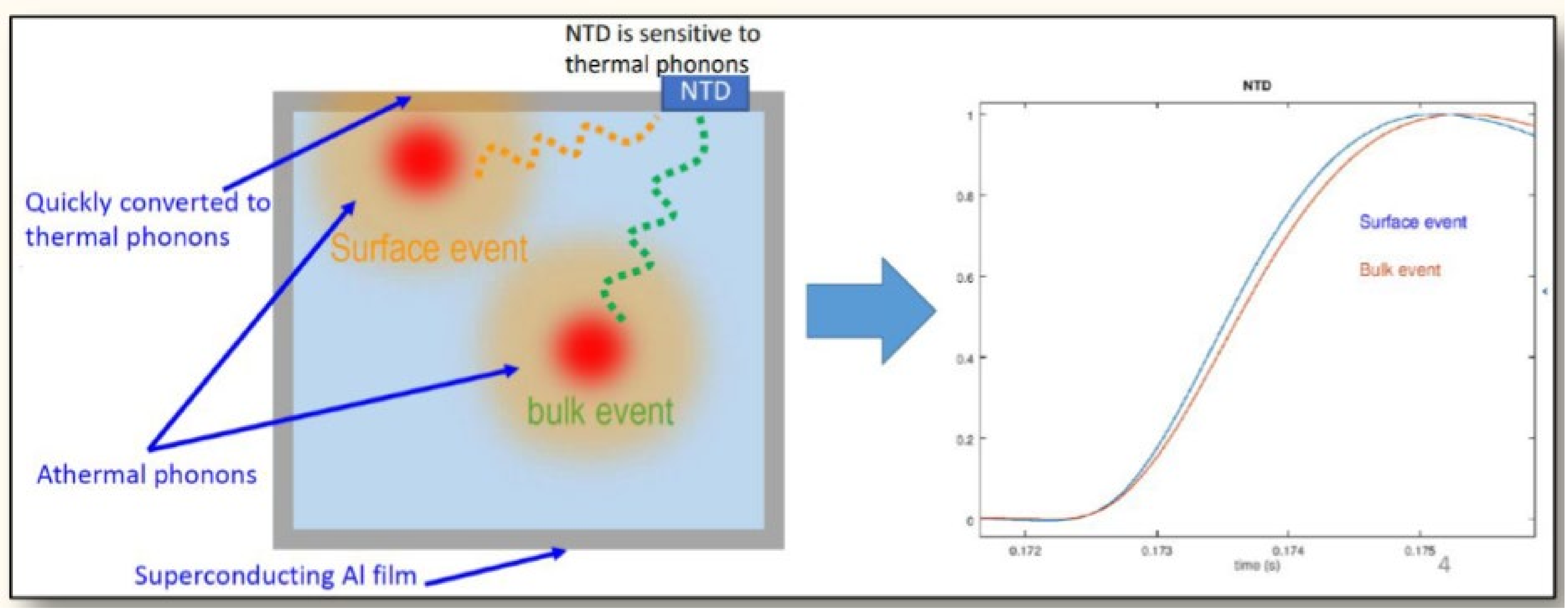
- The **infrastructure for CUPID** already **exists** (**CUORE** cryostat, **LNGS**, Italy)
- **Basic technology** demonstrated in **CUPID-Mo** (EDELWEISS cryostat, **Modane**, France)
- The **performance** of the single module and of the basic tower are validated
- **Crystallization** and **enrichement** at large scale are **possible** (Chinese production line)
- **Data-driven background model** indicates **b ~ 10^{-4} counts/(keV·kg·y)**
- **Neganov-Trofimov-Luke light detector** can mitigate the most challenging background
- **CROSS**: a standalone **competitive demonstrator** – test **crucial CUPID technologies**
- **CUPID can fully explore the inverted ordering region**
  down to $m_{\beta\beta}$ = 10 meV for the most favorable nuclear model
- **Staged deployment: CUPID Stage-I** can take data at the end of this decade and has **world leading science reach**
- **CUPID-1T: R&D required but clear directions** – approach the few meV region

BACK UP

CROSS project: discrimination of surface events

- Reject **surface events** by **Pulse Shape Discrimination assisted by metal film coating**

Metal films work as pulse-shape modifiers for charged particles that release energy close to the film (phonon and superconductivity physics)



Discrimination of surface events: results

After a long R&D with 2×2×1 cm^3 to fix the best coating material, **AlPd bi-layer** was selected

H. Khalife PhD thesis
https://theses.hal.science/tel-03168547

- Al is superconductive with T_C=1.2 K – Pd is a normal metal
- **Pd(10 nm) on the crystal – Al(100 nm) on top of Pd** $\rightarrow T_C \sim 0.7$ K (proximity effect)

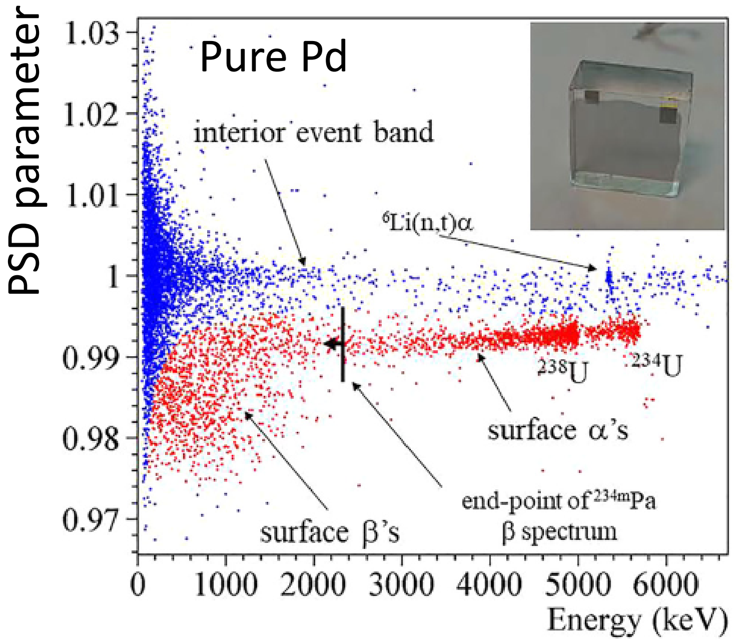
Best compromise between

- Efficient thermalization of surface events
- Low specific heat
- Easy deposition by evaporation

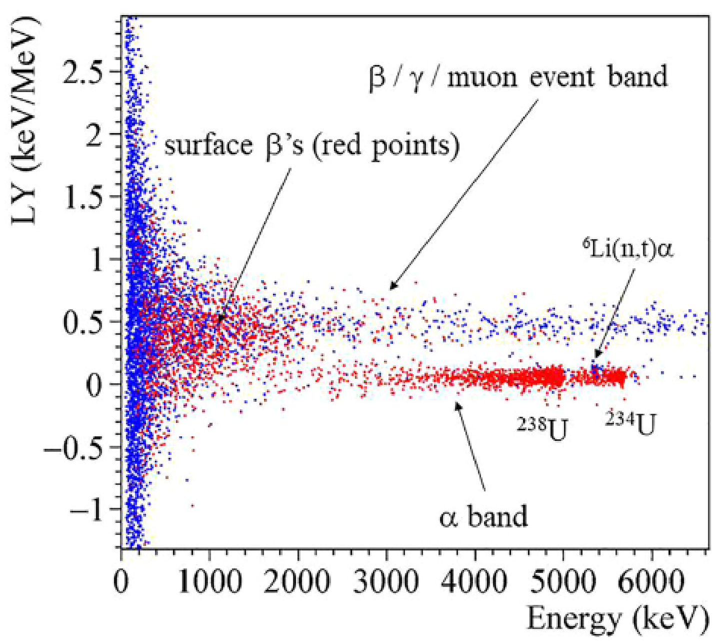
Sample are irradiated with an U source providing both α (4.2 and 4.7 MeV) and β (end-point at 2.2 MeV)

For redundancy, also scintillation light is detected

APL 118 (2021) 184105



Both surface α's and β's are discriminated by the metallic film

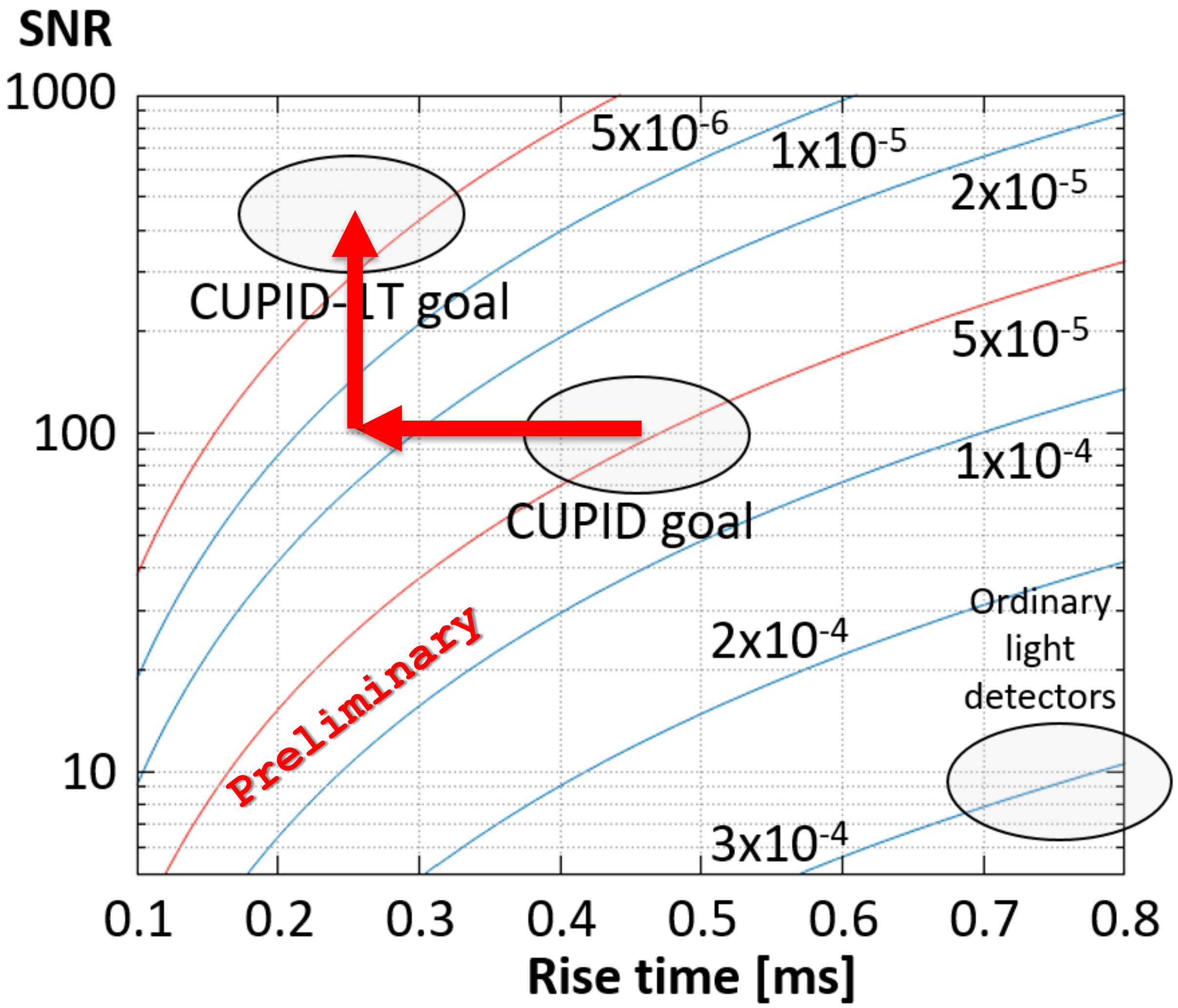


Only surface α's are discriminated by a light-yield cut

Unfortunately, technology transfer to large CUPID- and CROSS-size crystals (4.5 × 4.5 × 4.5 cm^3) failed so far

Is CUPID-1T feasible?

- **Pile-up**



Light detector performance

With respect to CUPID

- Increase SNR x5
- Reduce Rise-time x2

Two approaches under exploration

- Increase Li_2MoO_4 light emission by doping
- Change phonon sensor in light detector, moving to high impedance NbSi TES

- **Close components → a possible solution is the BINGO approach**

The BINGO experiment

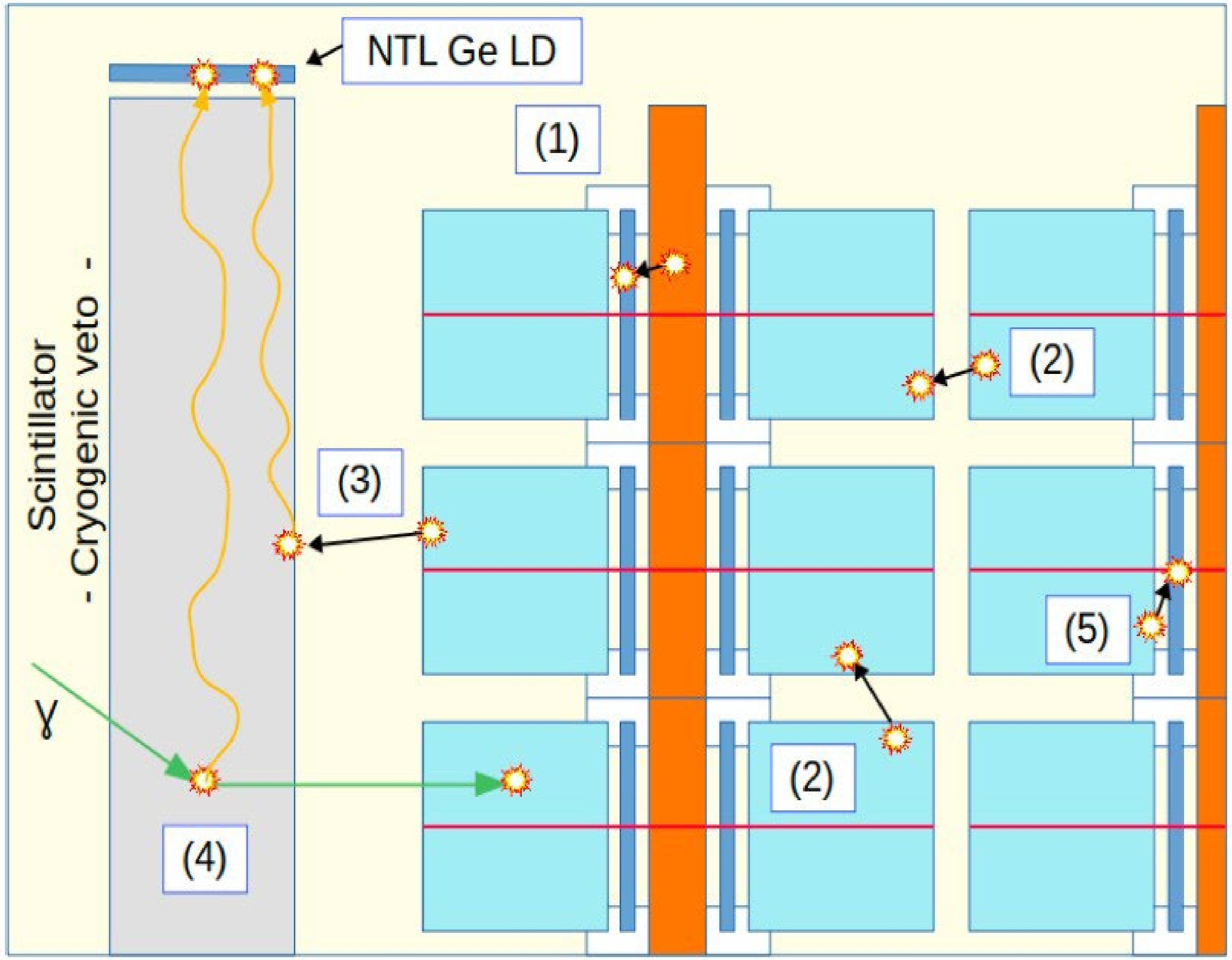
Bolometric search for $0\nu2\beta$ decay in ^{130}Te and ^{100}Mo

Demonstration of **3 innovative technologies:**

(1) Innovative detectors assembly:
Minimization of the amount of passive materials surrounding detectors to reduce α and β background from surface radioactivity

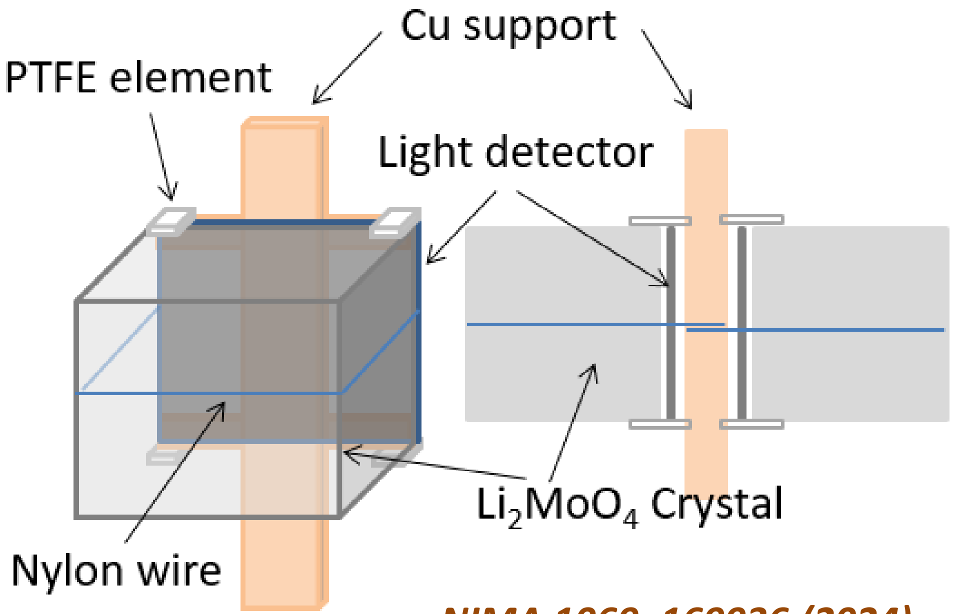
(2) Active cryogenic veto:
Suppression of background from high energy γ's surrounding detectors volume by a scintillator (BGO) operating at the base temperature

(3) Neganov-Luke light detectors:
Alpha background rejection (especially for TeO_2), pile-up rejection for LMO

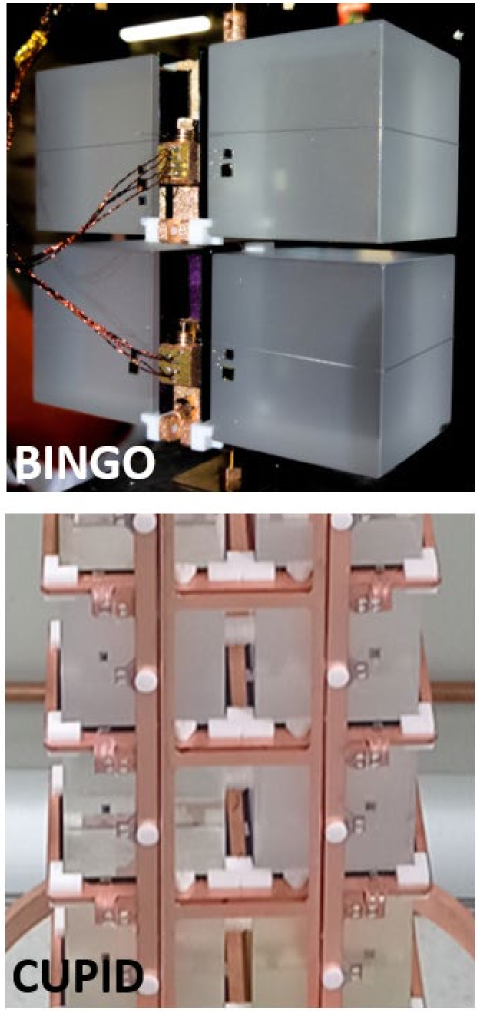


Surface background and BINGO

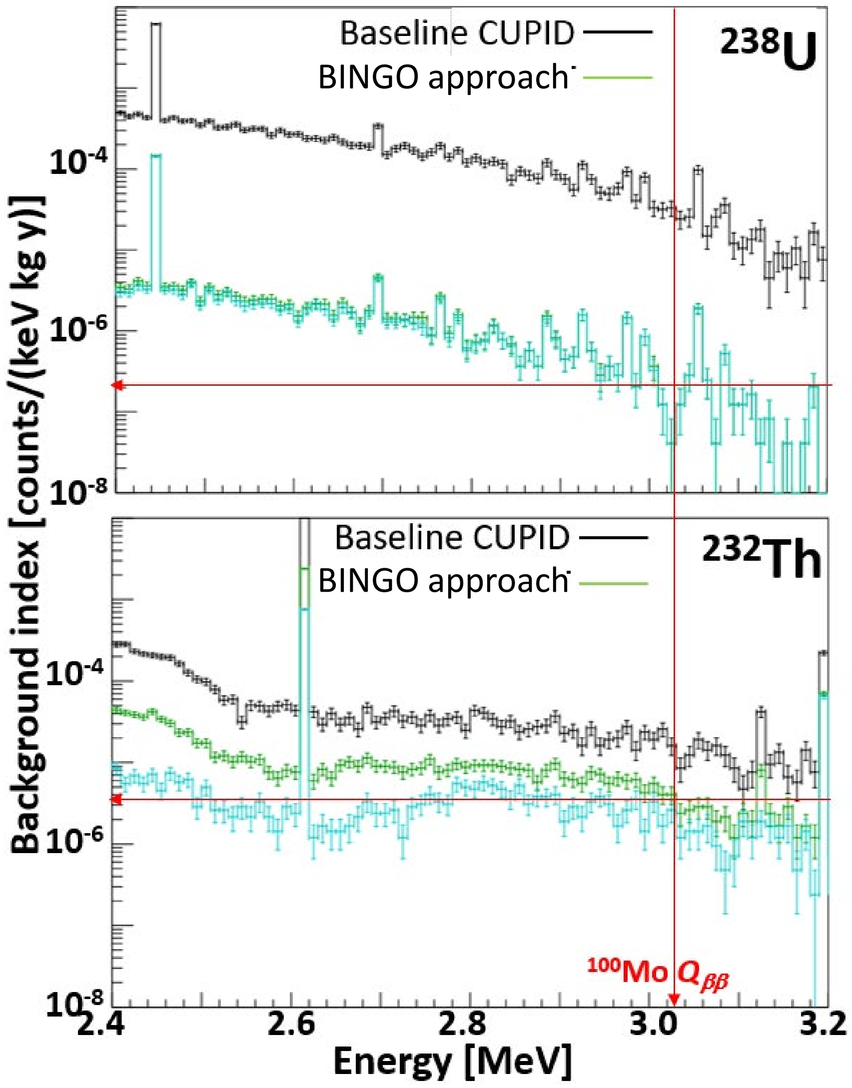
Mitigate background from Close components in CUPID



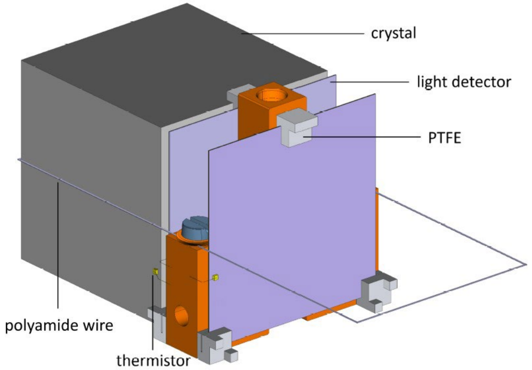
NIMA 1069, 169936 (2024)

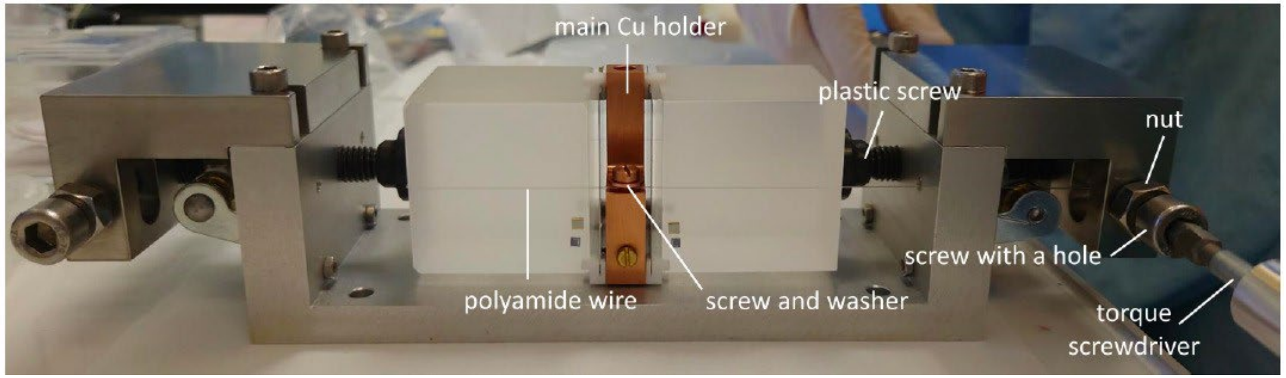


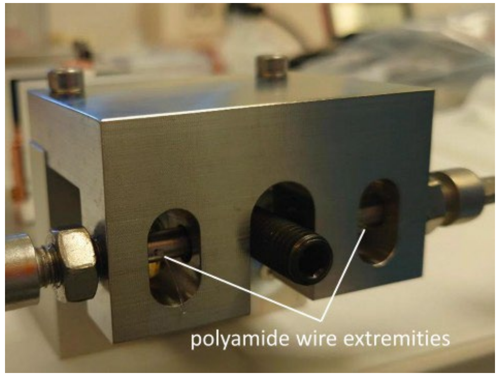
Simulation CUPID vs. BINGO



A revolutionary detector assembly

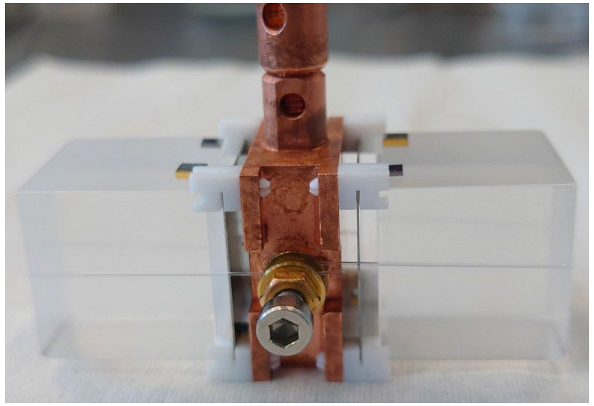




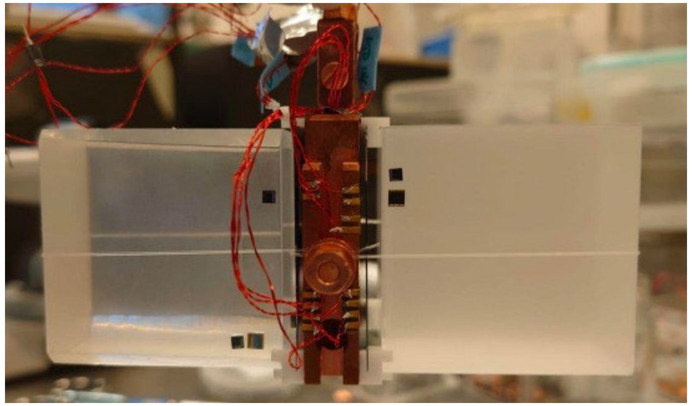


Polyamide wires are tensioned like violin strings at 4 + 4 kg

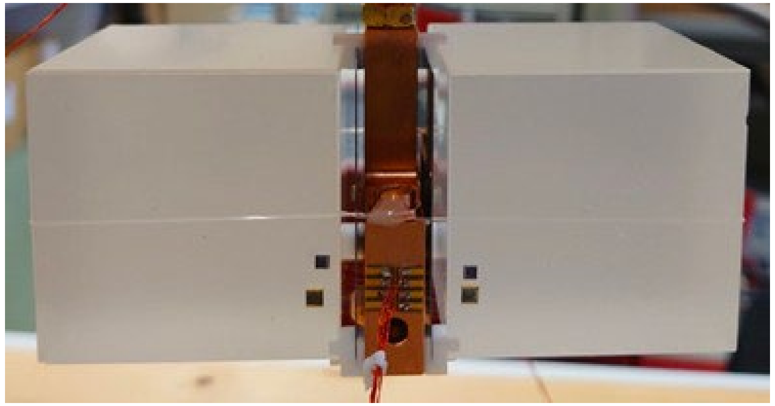
First prototype with small LMO crystals



Full-size LMO crystals

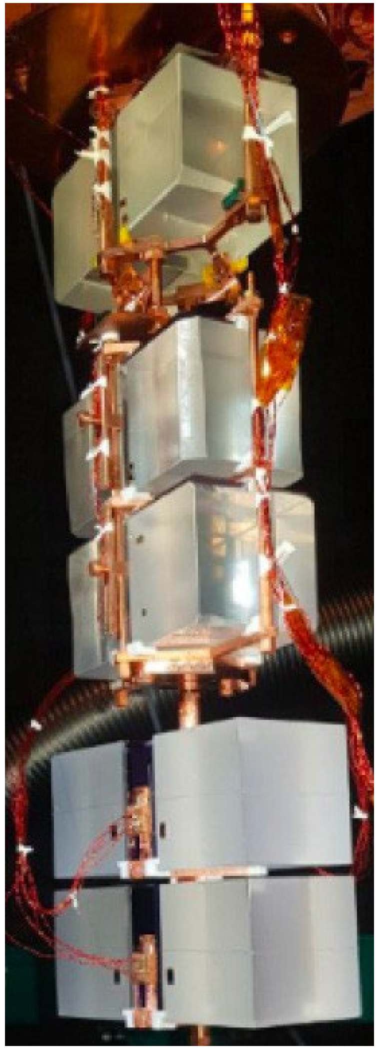


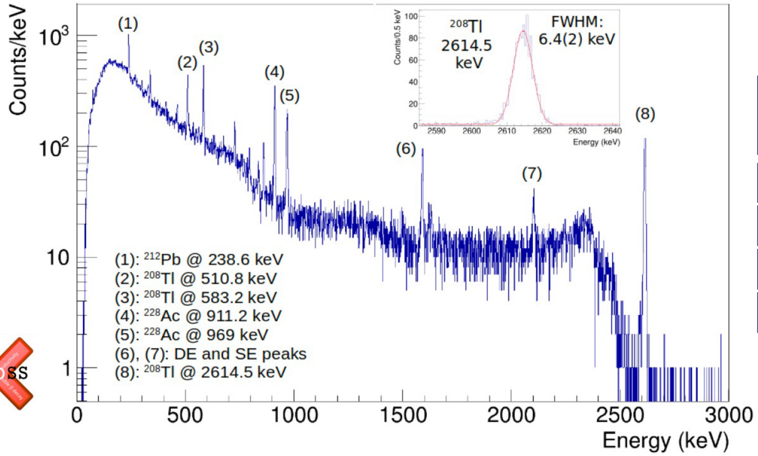
Full-size TeO_2 crystals

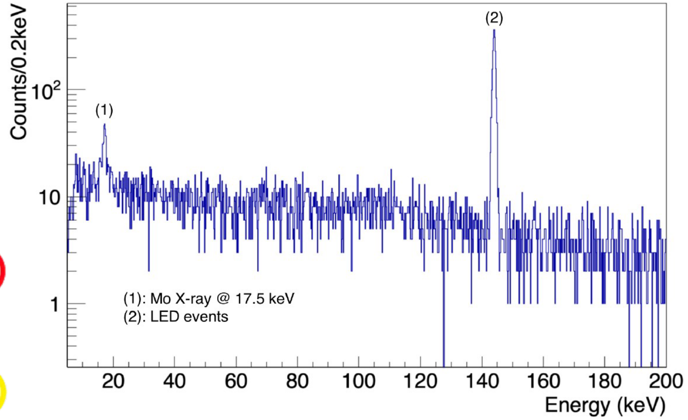


All the assembly prototypes were tested at the base temperature 15-20 mK above ground @IJCLab

BINGO detectors work!







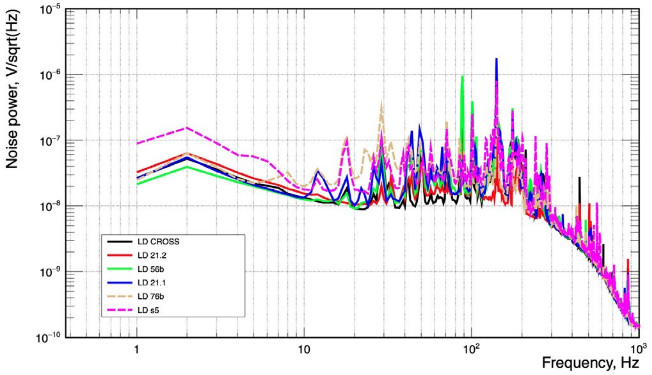
LMO crystals performance

Detector	Sensitivity, nV/keV	FWHMbsl, keV	FWHM2615, keV
LMO-1	31	2.5	7.1(4)
LMO-2	85	1.5	5.6(2)
LMO-3	57	4.6	6.0(4)
LMO-4	44	2.6	6.6(4)

- Good energy resolution close to ROI: around **6 keV FWHM at 2615 keV**
- Performance of BINGO modules is similar to results of CROSS LMOs

LDs performance

Detector	Sensitivity, uV/keV	FWHMbsl, keV
LD-1	1.0	0.24
LD-2	1.7	0.16
LD-3	1.8	0.21
LD-4	1.3	0.26



- **Around 0.2 keV FWHM noise**, which guarantees efficient particle identification
- Noise power spectra are similar to the reference LDs of CROSS

Multi-isotope search

In case of discovery in one isotope, **confirmation is needed with more isotopes**
→ Precision measurement era in $0\nu2\beta$ study – mechanism and NMEs
→ The bolometric technique is perfectly adapted to this task

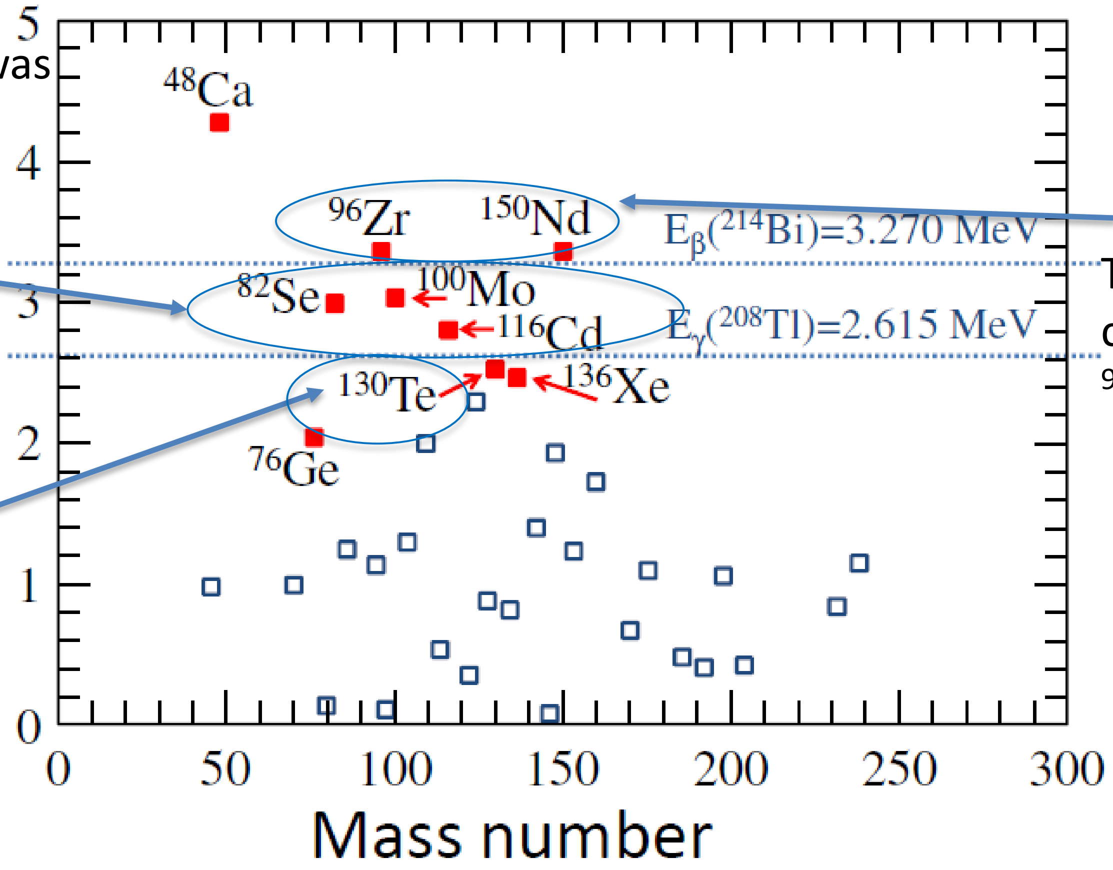
Scintillating bolometer technology was successfully applied to
^{82}Se (ZnSe – **CUPID-0** experiment)
^{116}Cd ($CdWO_4$)

Phys. Rev. Lett. 129, 111801
JLTP 199, 467 (2020)

In addition, TeO_2 bolometers can be improved with the **detection of Cherenkov light** for the rejection of α background (NTL light detectors)

Phys. Rev. C 97, 032501(R) (2018)

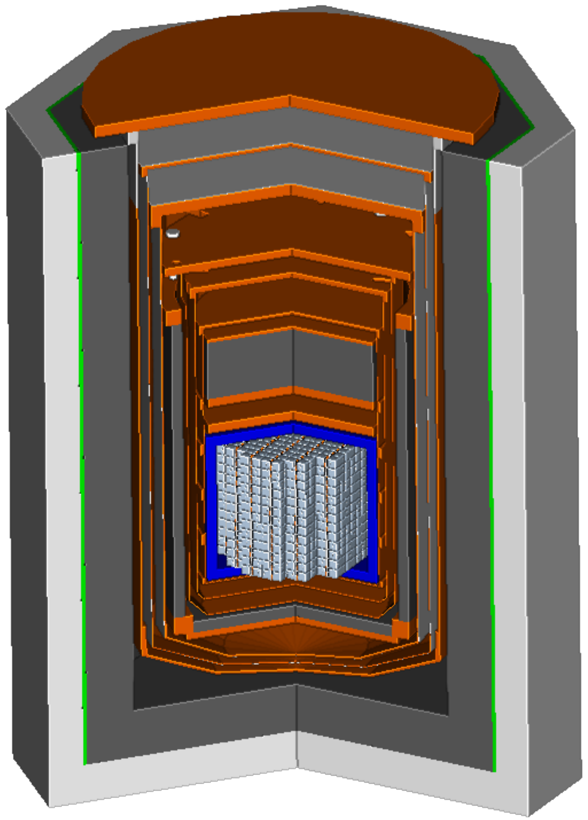
Eur. Phys. J. C (2018) 78: 272



The **TINY project** studies the challenging development of ^{96}Zr-and ^{150}Nd-based bolometers

A. Zolotarova, NEUTRINO 2024

CUPID BG projection



Cryostat and Background model
Phys. Rev. Lett. 126, 171801 (2021)
Phys. Rev. D 110, 052003 (2024)
arXiv:2509.05528

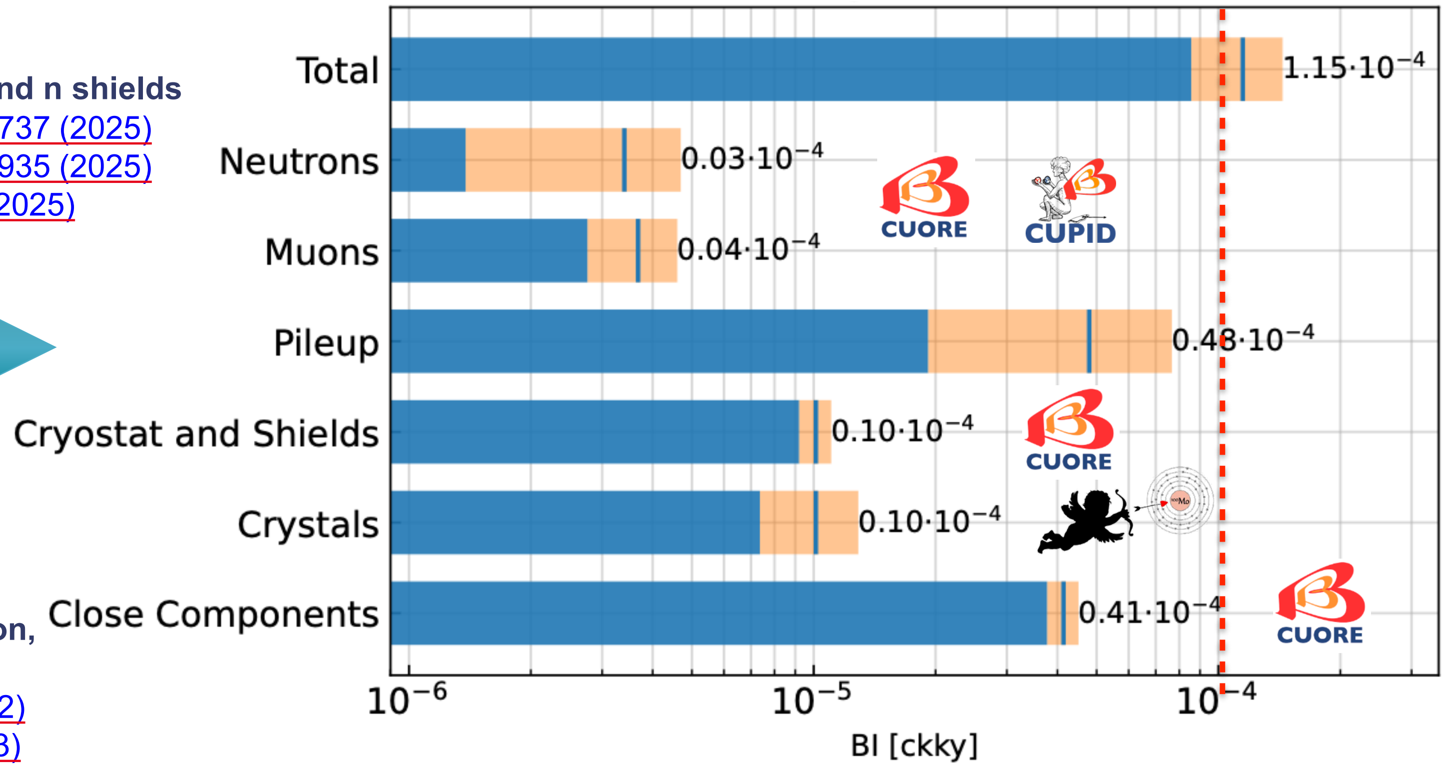
Tower design, μ and n shields
Eur. Phys. J. C 85, 737 (2025)
Eur. Phys. J. C 85, 935 (2025)
JINST 20 P08020 (2025)

GEANT4

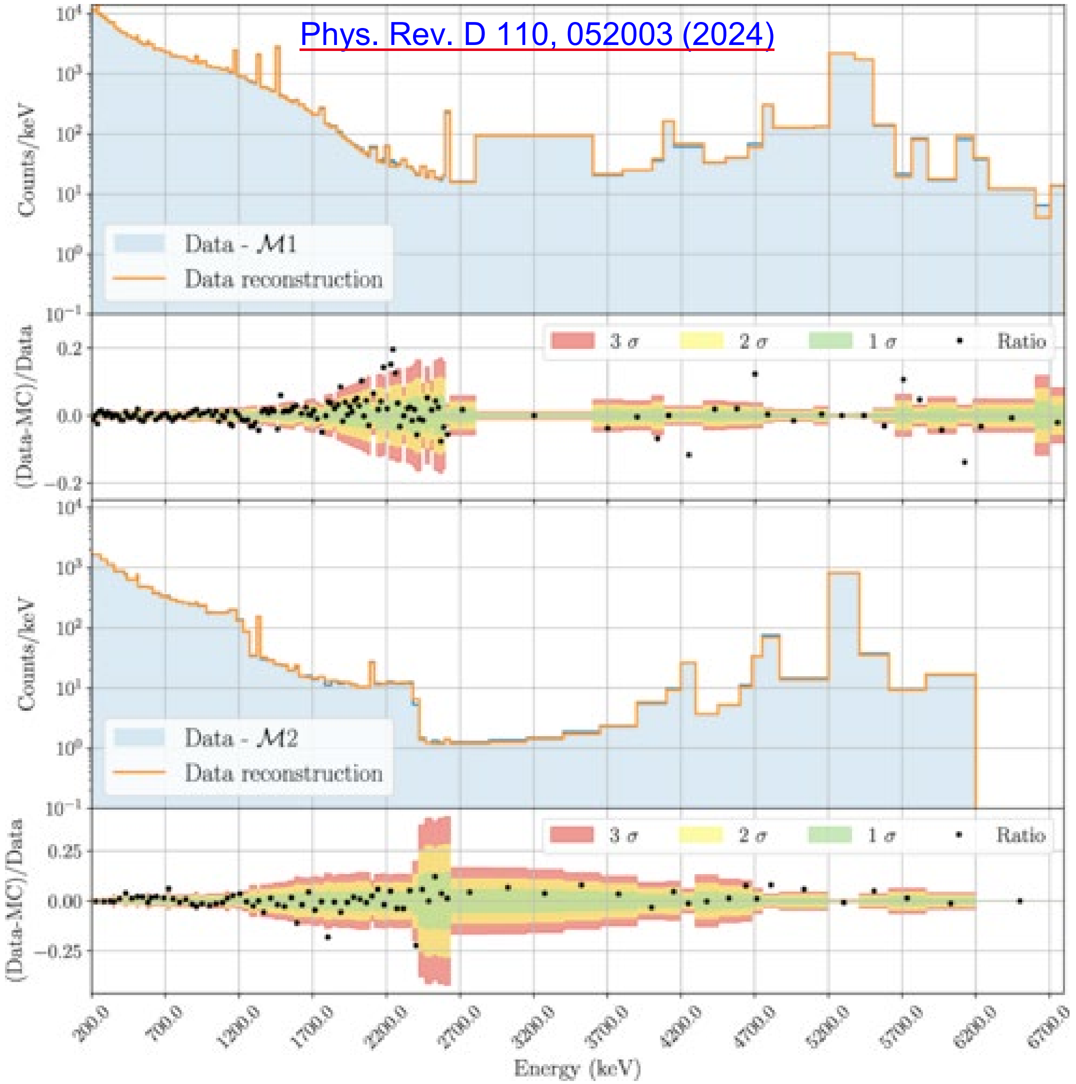
Li_2MoO_4 crystals & α rejection, pile-up
Eur. Phys. J. C 82, 1033 (2022)
Eur. Phys. J. C 83, 675 (2023)
Phys. Rev. Lett. 131, 16250 (2023)
arXiv:2507.15732v1 (2025)

CUPID-0
Scintillating bolometer & α rejection

CUPID BG simulation

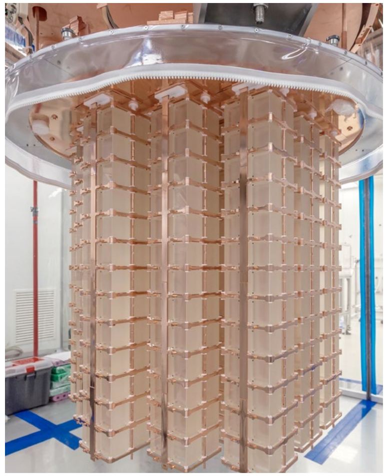


CUORE BG model - input for CUPID



CUORE Background model

- **In-situ background assessment of the infrastructure for CUPID!**
- 7 source locations,
  46 bulk sources (partial decay chains, location)
  47 surface sources (partial decay chains, depth, location)
- Uses pre-screening geometric information, time information, event topology (M1, M2, priors where reliably available)
- Overall very good agreement with data

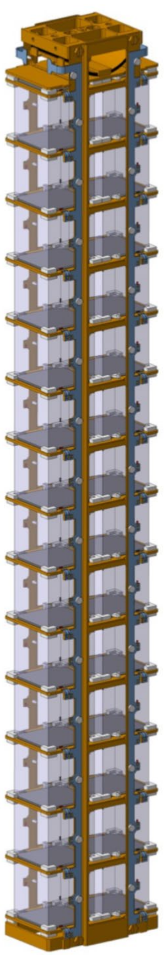


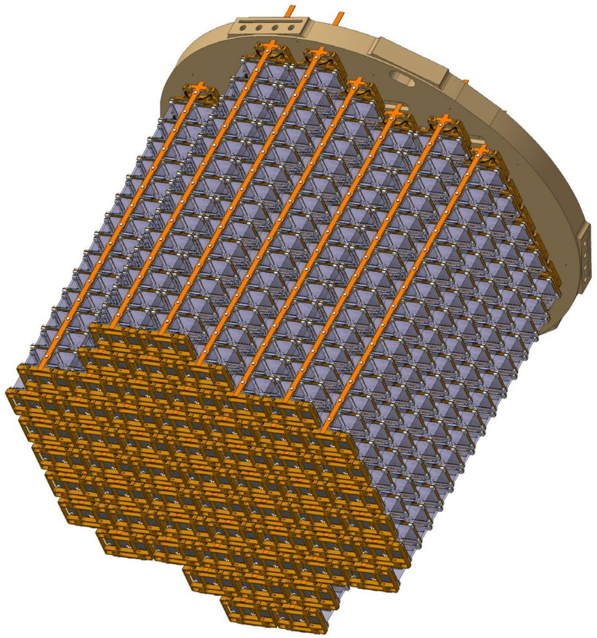
Surface α contaminations dominant!

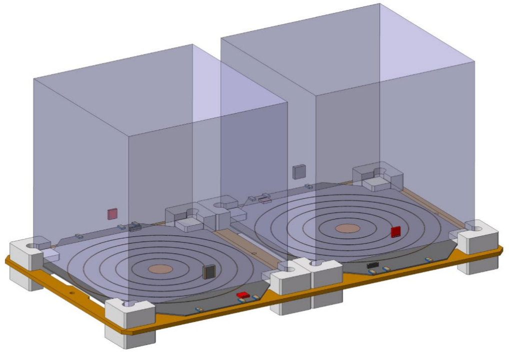
From CUORE to the CUPID Bg model

[Eur. Phys. J. C 85, 737 (2025)](#)
[Eur. Phys. J. C 85, 935 (2025)](#)

[arXiv:2509.05528](#)
[JINST 20 P08020 (2025)](#)





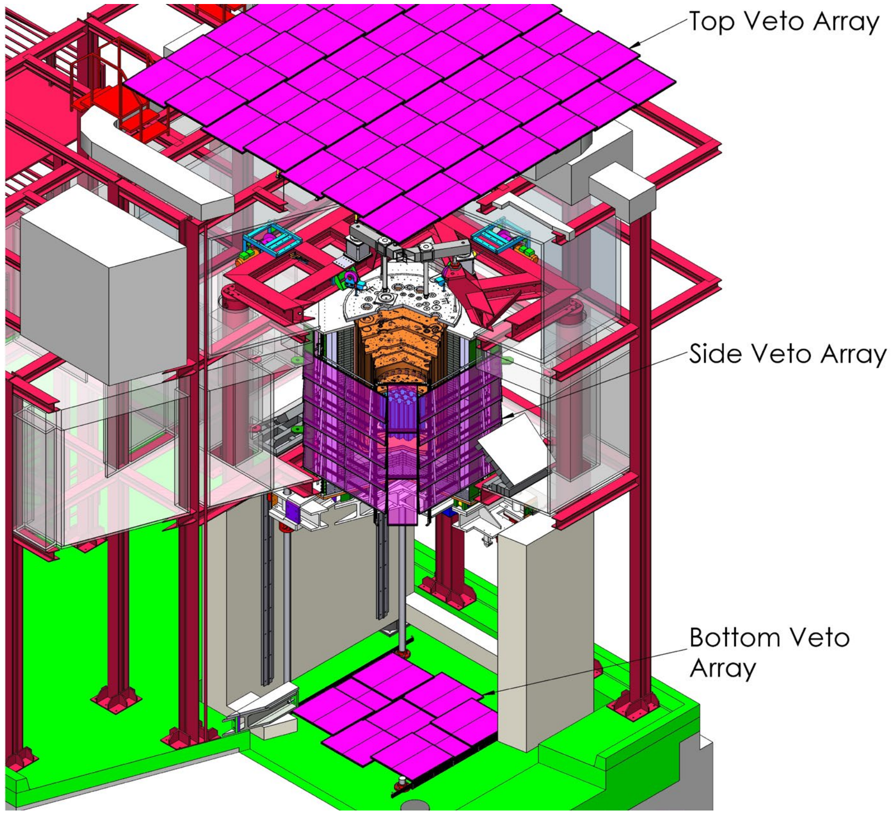


CUPID Background model

- CUORE infrastructure
- + New detector array:
  Scintillating detectors
  Full detector response model
- Muon veto system
- Extra neutron shielding

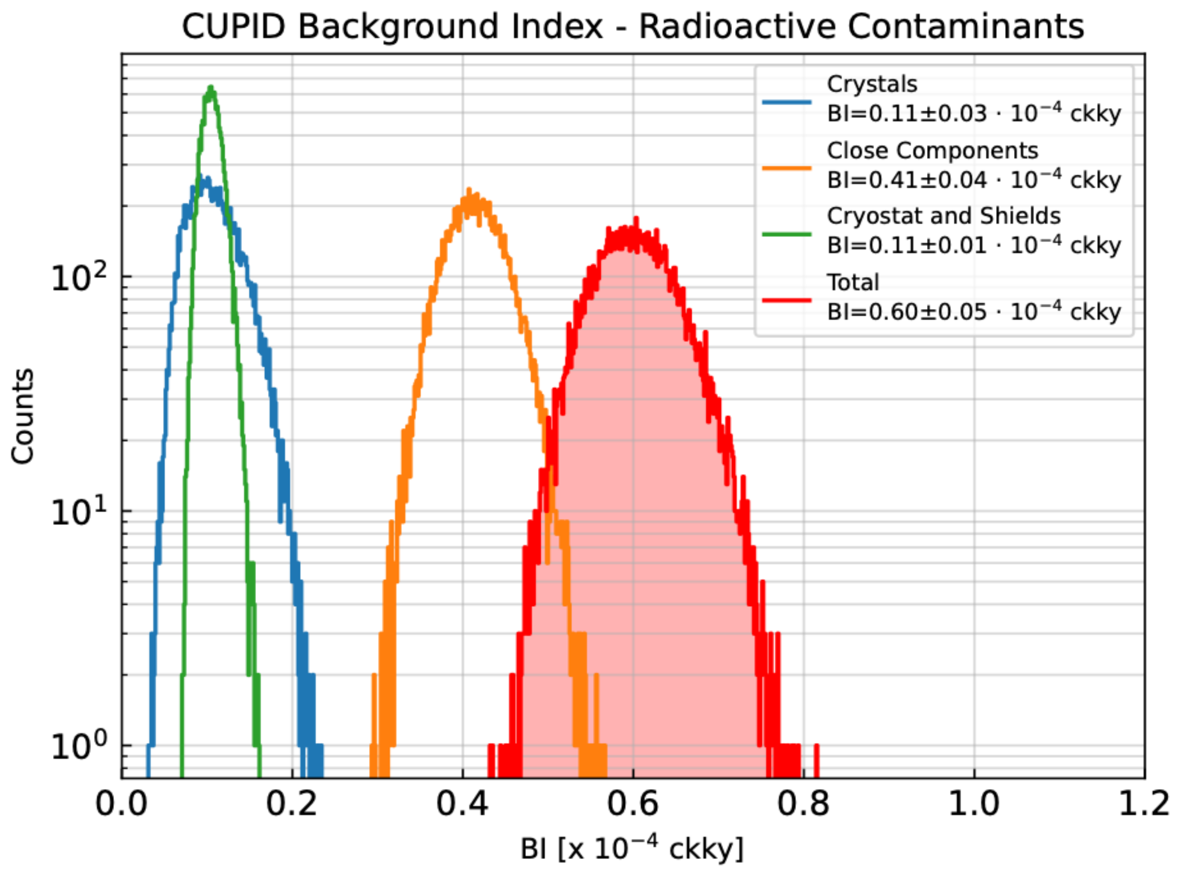
Geant 4 for radiogenic and muons

MCNP for neutrons (n,γ)
+Prompt gammas in Geant 4
with full custom detector response



Robust data-driven background predictions
Software/Techniques validated in situ on CUORE data

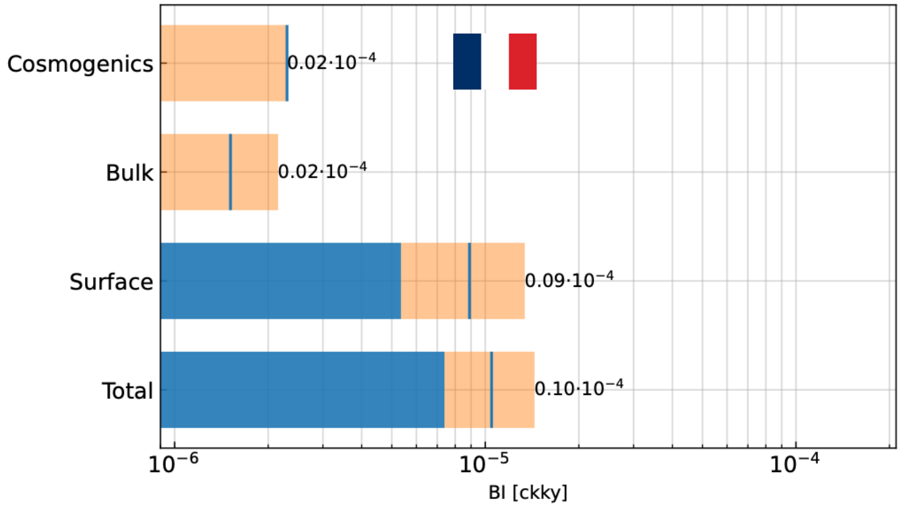
CUPID BG projection - Radiogenics



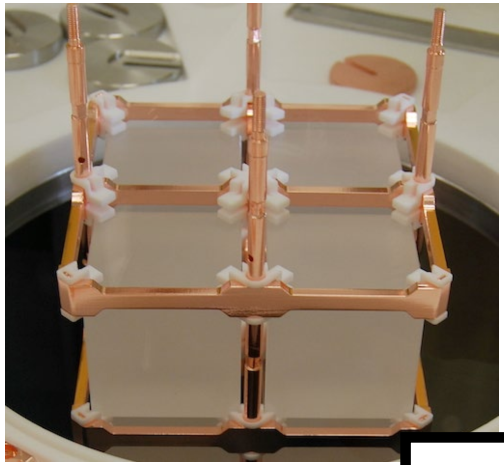
For CUPID: After surface α removal:
Surface β contaminations remain very important!

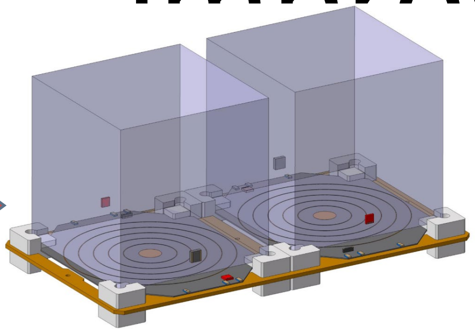
Cosmogenic activation

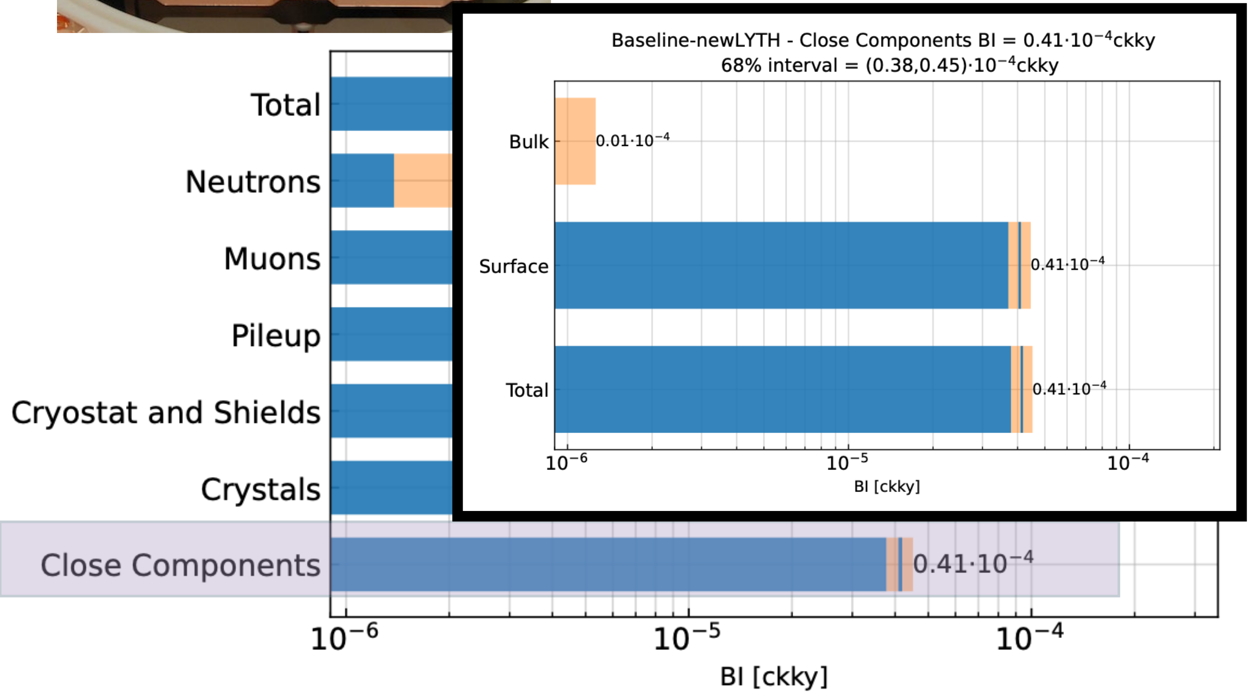
- 3 month at sea level, 1 yr underground before data taking
  - No transport by airplane
  - Crystals will be delivered in batches and stored underground at LNGS significantly increasing the storage ("cool down") time for most crystals
- Negligible Background from underground activation

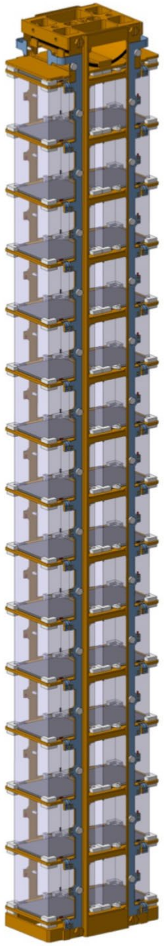


CUPID BG projection - Design improvements



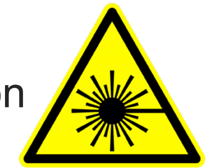






Improvements to be evaluated:

- New simplified mechanical tower design: less machining & handling
  - Lamination + contact-less production with laser cutting
  - No shadowing during etching/cleaning
- Improved radiopurity protocols during construction & storage

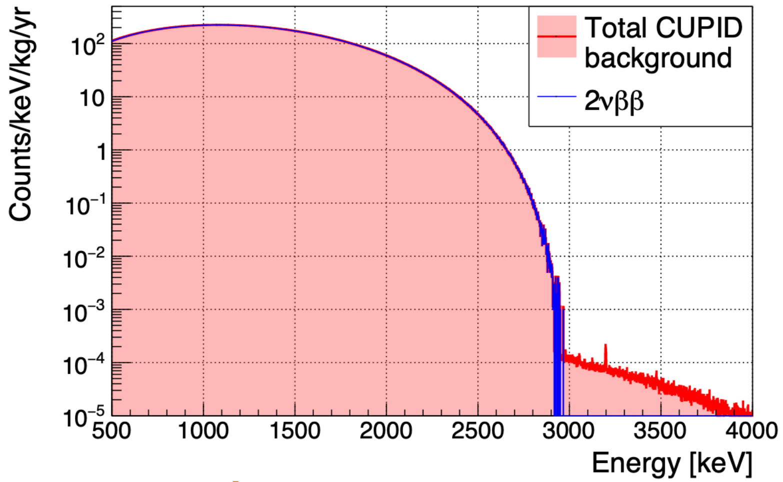


New screening campaigns to qualify surface backgrounds of machined pieces of CuPEN/PTFE/Copper ongoing

Target:
1/2 contamination compared to CUORE

CUPID: Pile-up background challenge

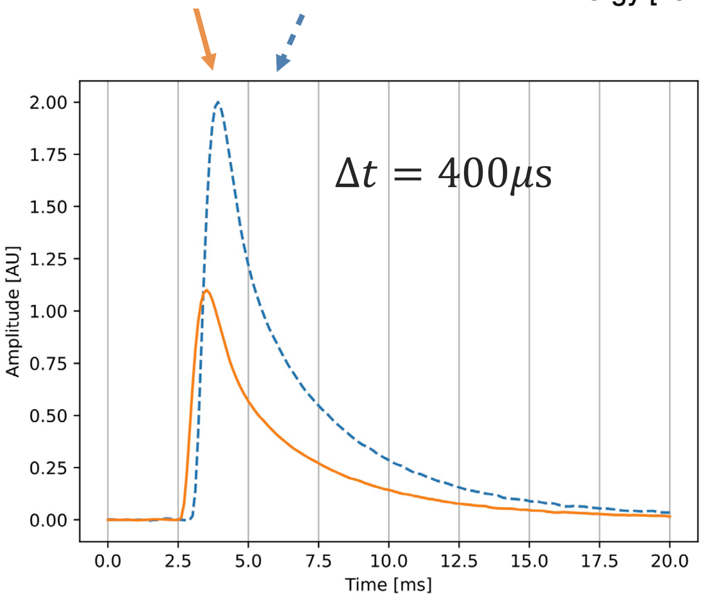
Phys. Rev. Lett. 131, 16250 (2023) $T_{1/2} = 7.1 \cdot 10^{18}\text{yr}$



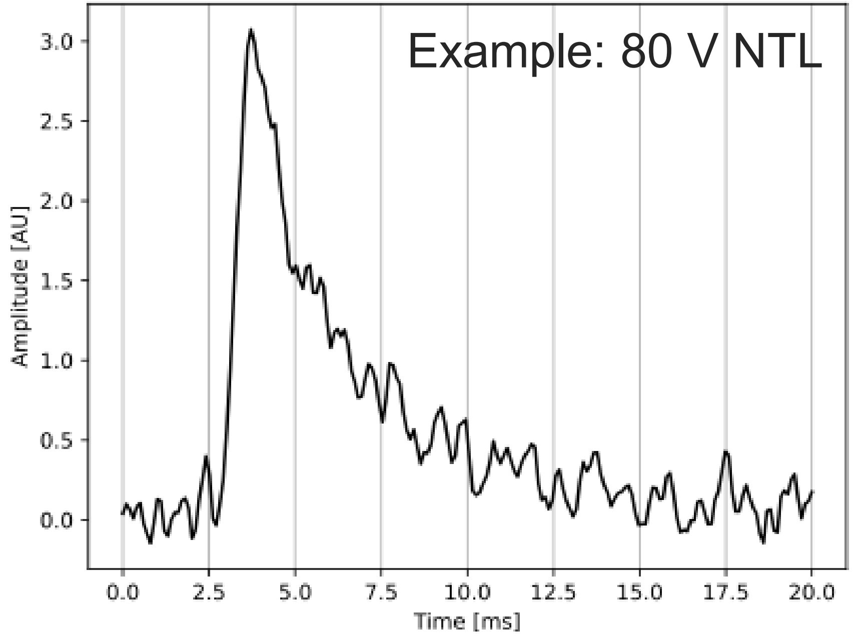
Simulations in addition to experimental testing:

Background prediction for pile-up

Randomly sample coincidences from the CUPID background model

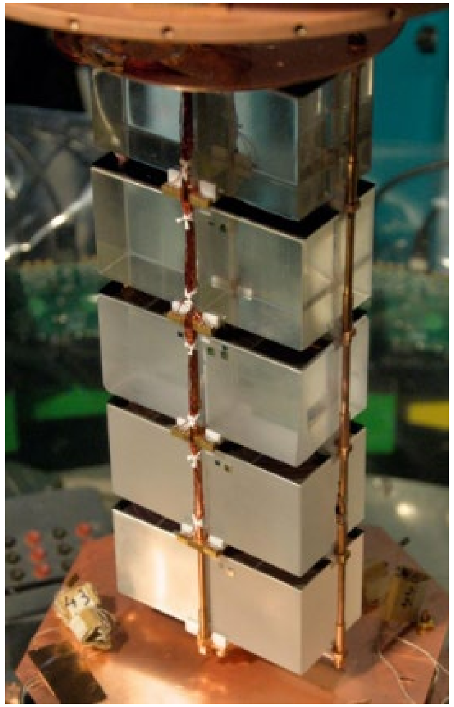


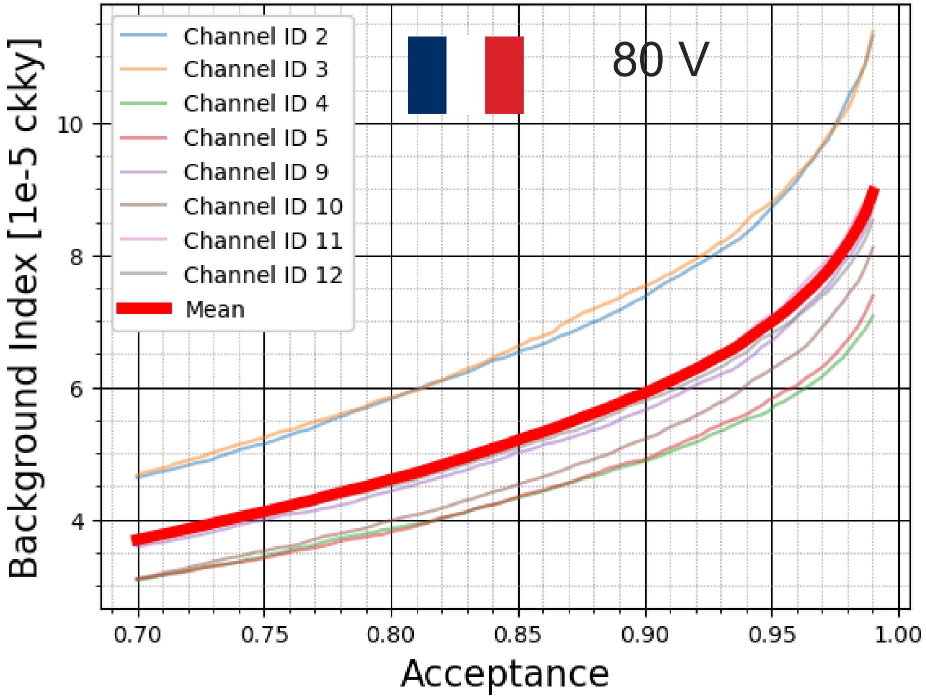
Vary time separation & add measured noise



CUPID - Improvements: NTL light detectors

[EPJ-C 74,2913 (2014)](#)
[EPJ-C 77, 3 (2017)](#)
[NIM A 940, 320 (2019)](#)
[EPJC 83, 373 (2023)](#)
https://arxiv.org/abs/2507.15732v1 (2025)

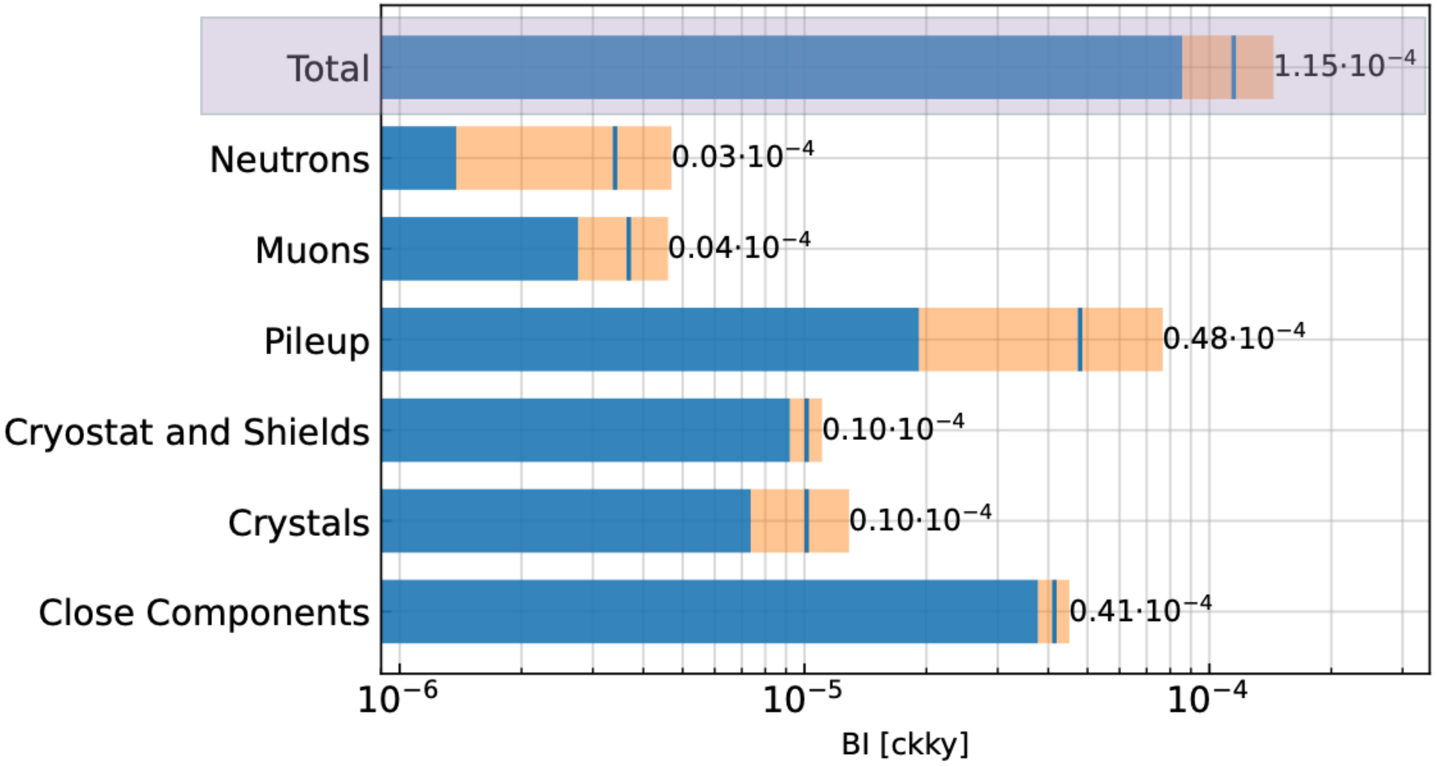




- Over 10 yrs of pile-up background characterisation and NTL detector development in France (Subset of publications on the left)
- Transfer of NTL technology to US for risk mitigation and production schedule
- Recent progress (2025)
  - Detailed control and optimisation of ANPS is very important
  - Analysis techniques:
    - Gained 28% improvement on BI with respect to OF (16% with respect to arXiv:2507.15732)
- Full electrode coverage to improve gain by ~25% in reach
- Full pre-testing to use higher NTL voltage
- New results (CROSS & VSTT) imminent

NTL light detectors ->Pile-up can be reduced to less than 5 x 10^{-5} counts/keV/kg/yr

CUPID BG projection - Summary



Conservative prediction

1 σ range: [0.86, 1.44] 10^{-4} counts/keV/kg/yr

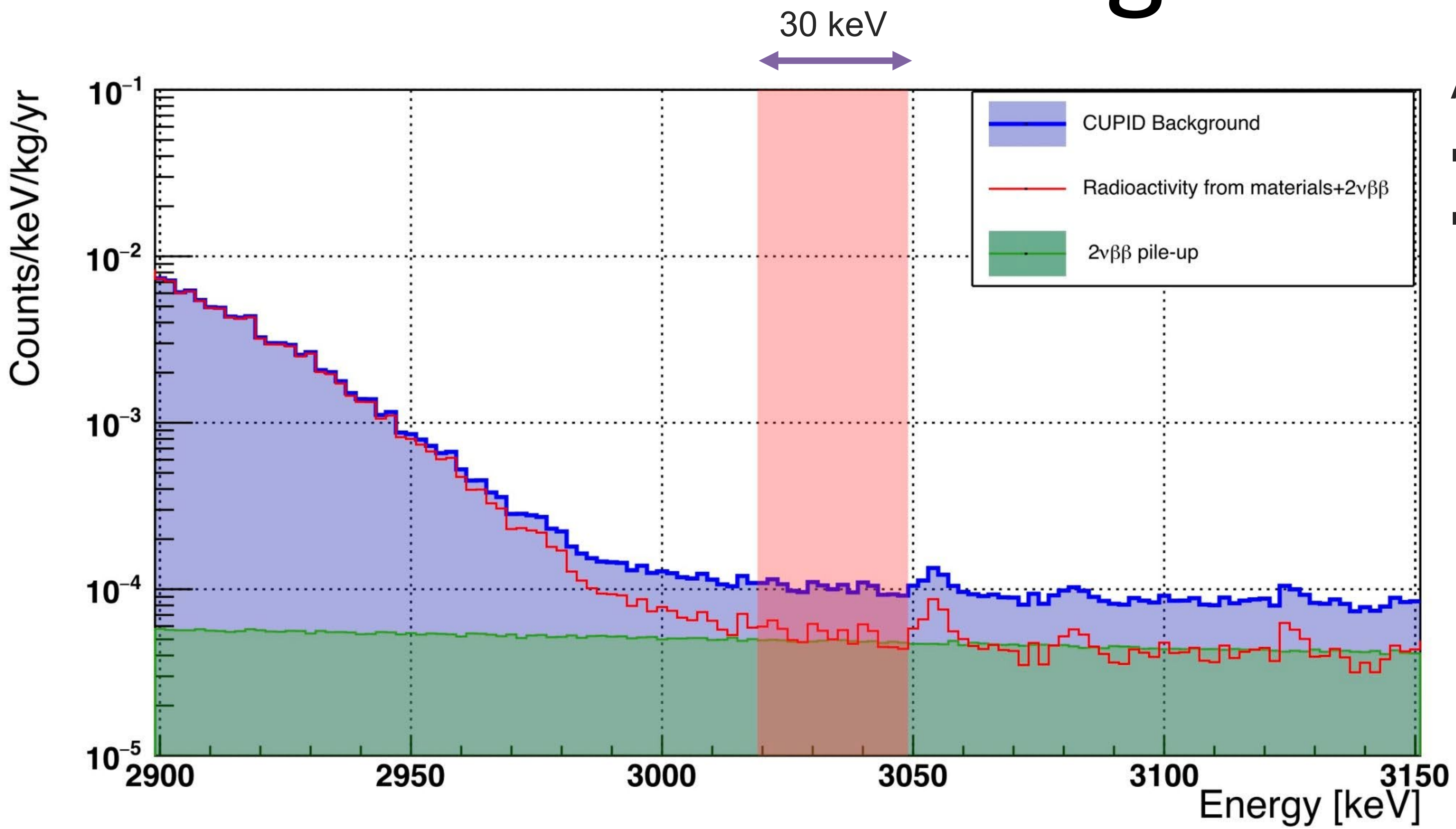
Improvements expected by experiment construction

- Pile-up (Analysis ML / LD design)
- Surface contamination levels for close components
- Delayed coincidence tags - Extension to NR tagging

CUPID's background projections are robust using in-situ characterisation and conservative assumptions

10^{-4} counts/keV/kg/yr as project target or better are in reach

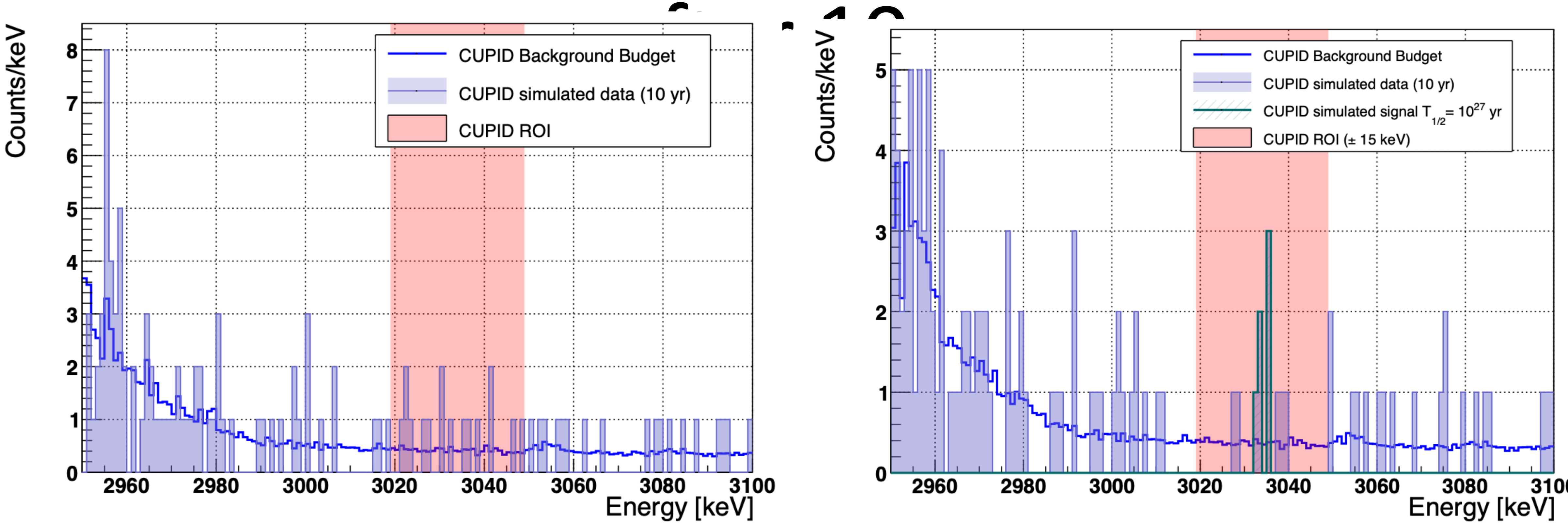
CUPID ROI - Background shape



Analysis

- ^{100}Mo: $Q_{\beta\beta} = 3034\text{keV}$
- Excellent energy resolution
  - Target: 5 keV FWHM
  - We expect no influence from the $2\nu\beta\beta$ endpoint
  - Both $2\nu\beta\beta$ pile-up and radiogenic contributions show a flat spectrum in the ROI
  - Expect a very clean analysis!

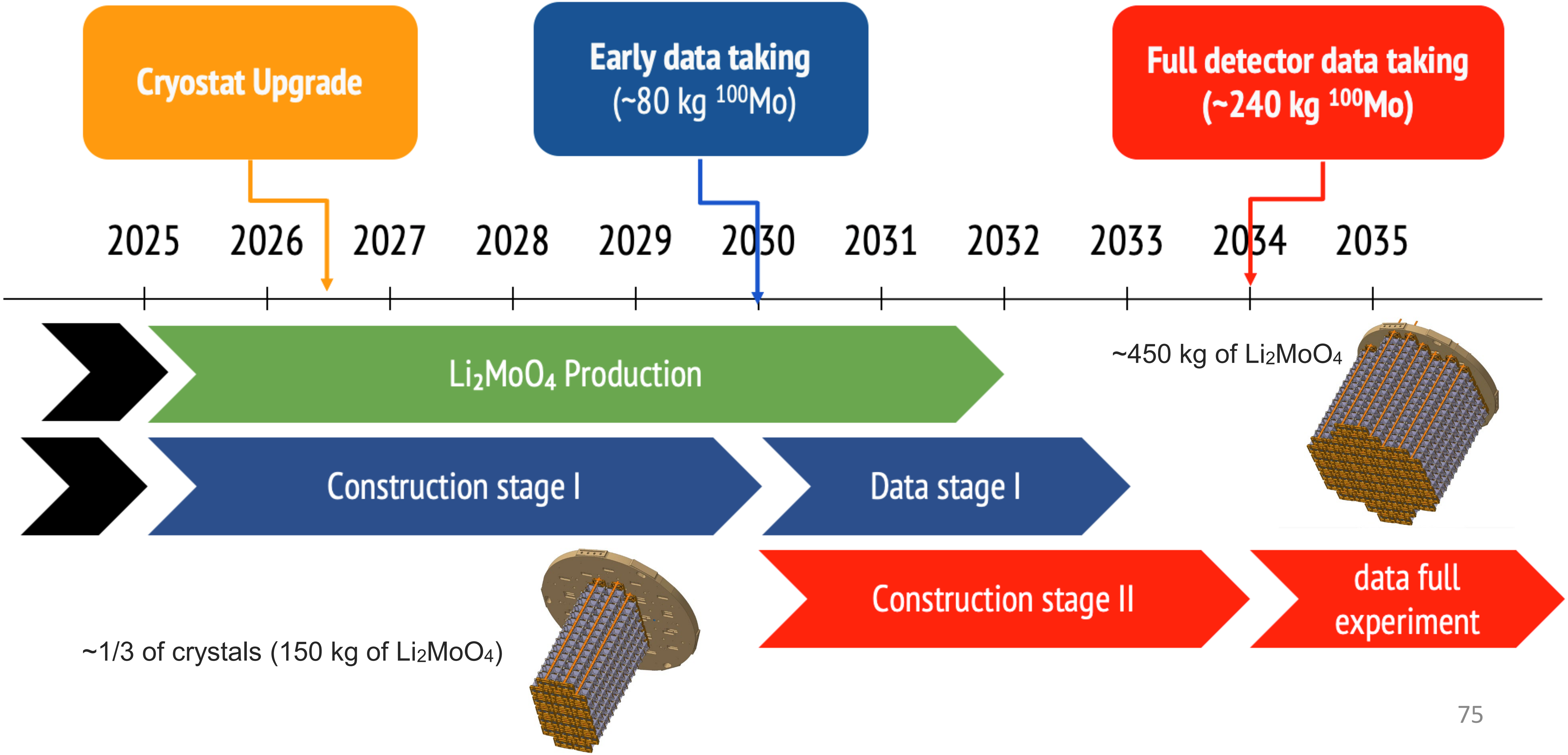
CUPID ROI - Background and Signal



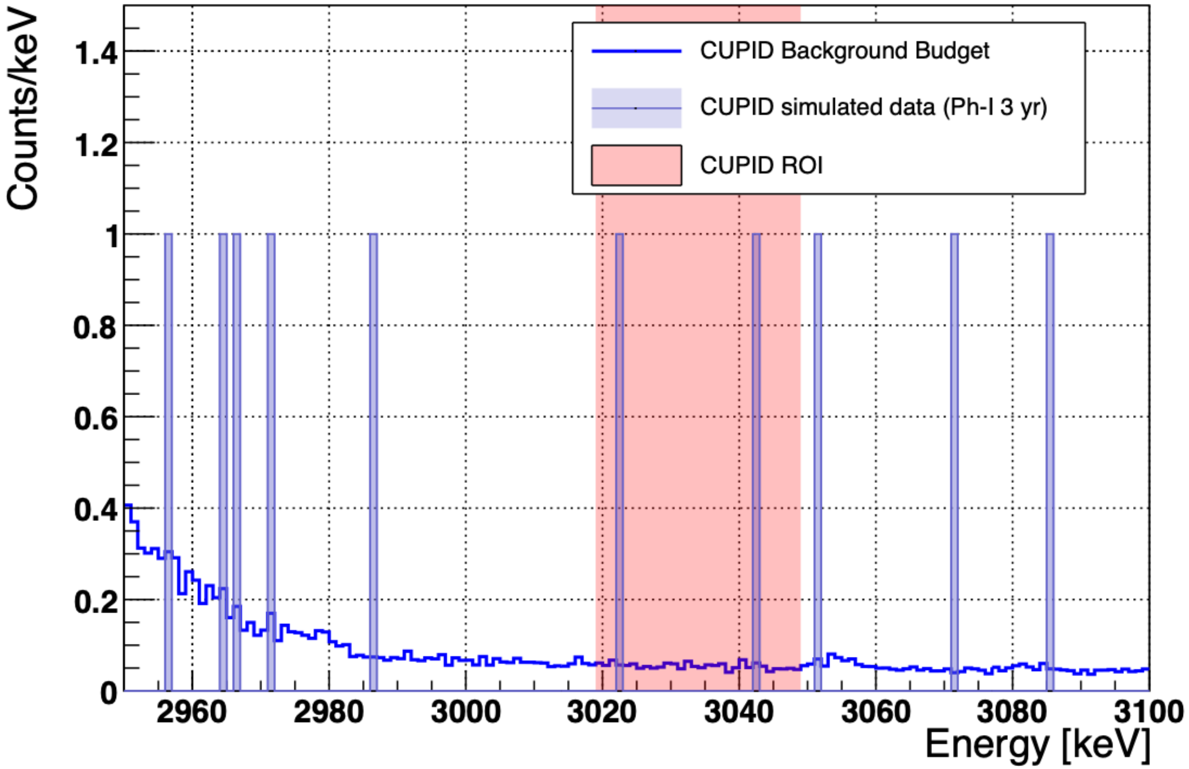
CUPID is a discovery experiment with a clear peak signature over a flat background
Median 3 σ discovery sensitivity of 10^{27}yr

Bonus: $2\nu\beta\beta$ dataset with O(10^{10}) events: Excellent potential for nuclear physics and precision studies

CUPID Timeline



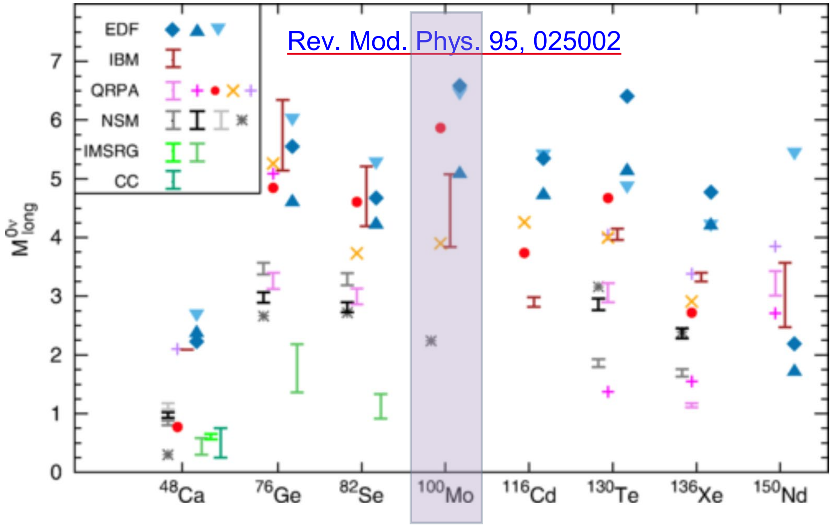
CUPID ROI - Stage I after 3 yr

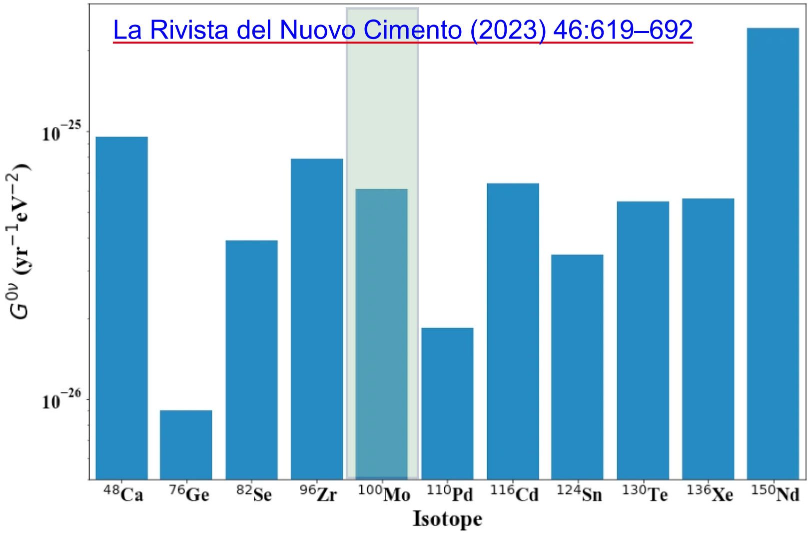


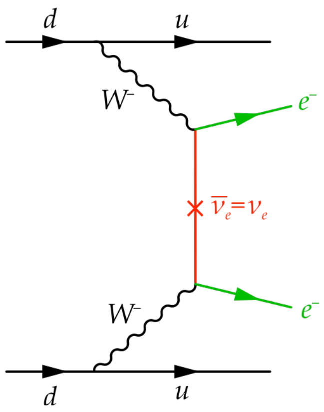
CUPID Phase-I is quasi background free BI = ~1.5 x 10^{-4} counts/keV/kg/yr:

- With 5 keV FWHM expect less than 1 background event in $\pm 3\sigma$ range around $Q_{\beta\beta}$
- Median 3 σ discovery sensitivity (3 yr) of 2 x 10^{26} yr

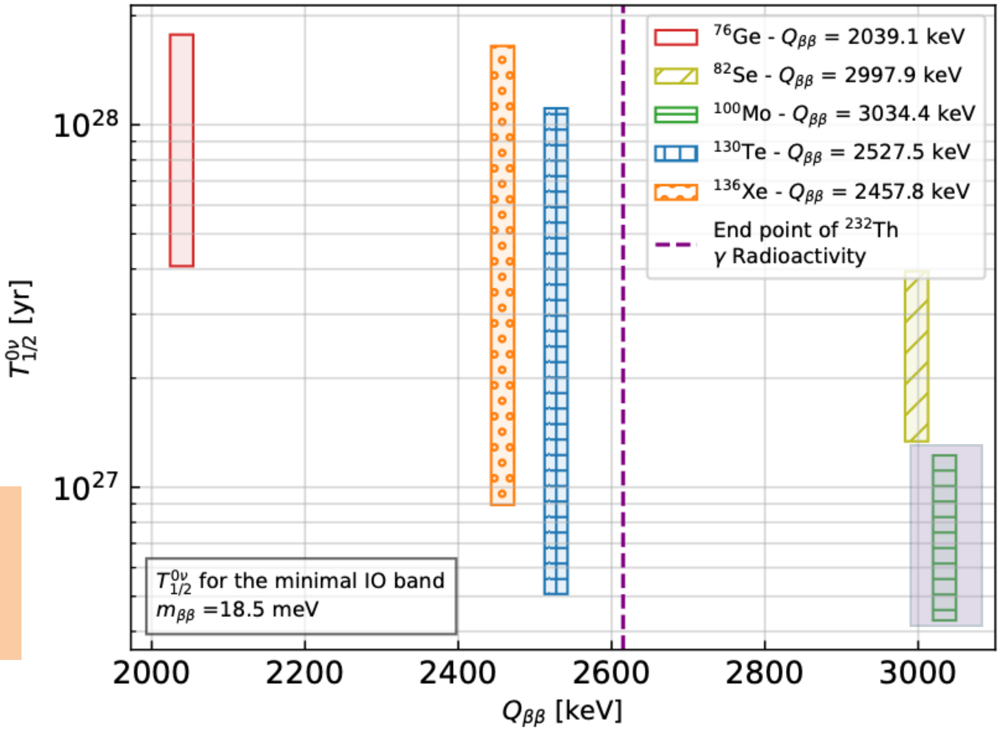
From half-life to effective Majorana mass (Light Majorana neutrino exchange)







$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

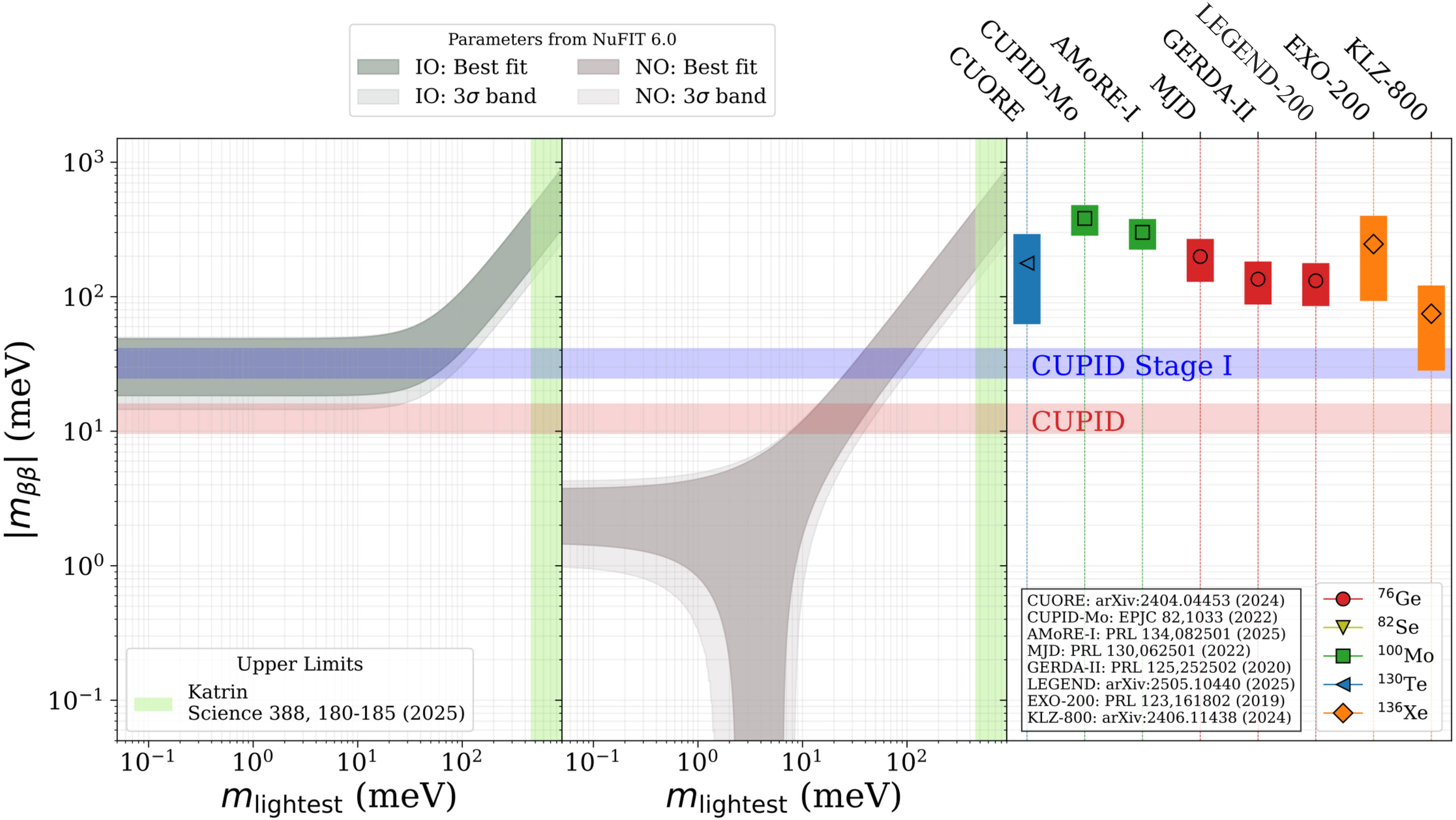


Effective Majorana mass:

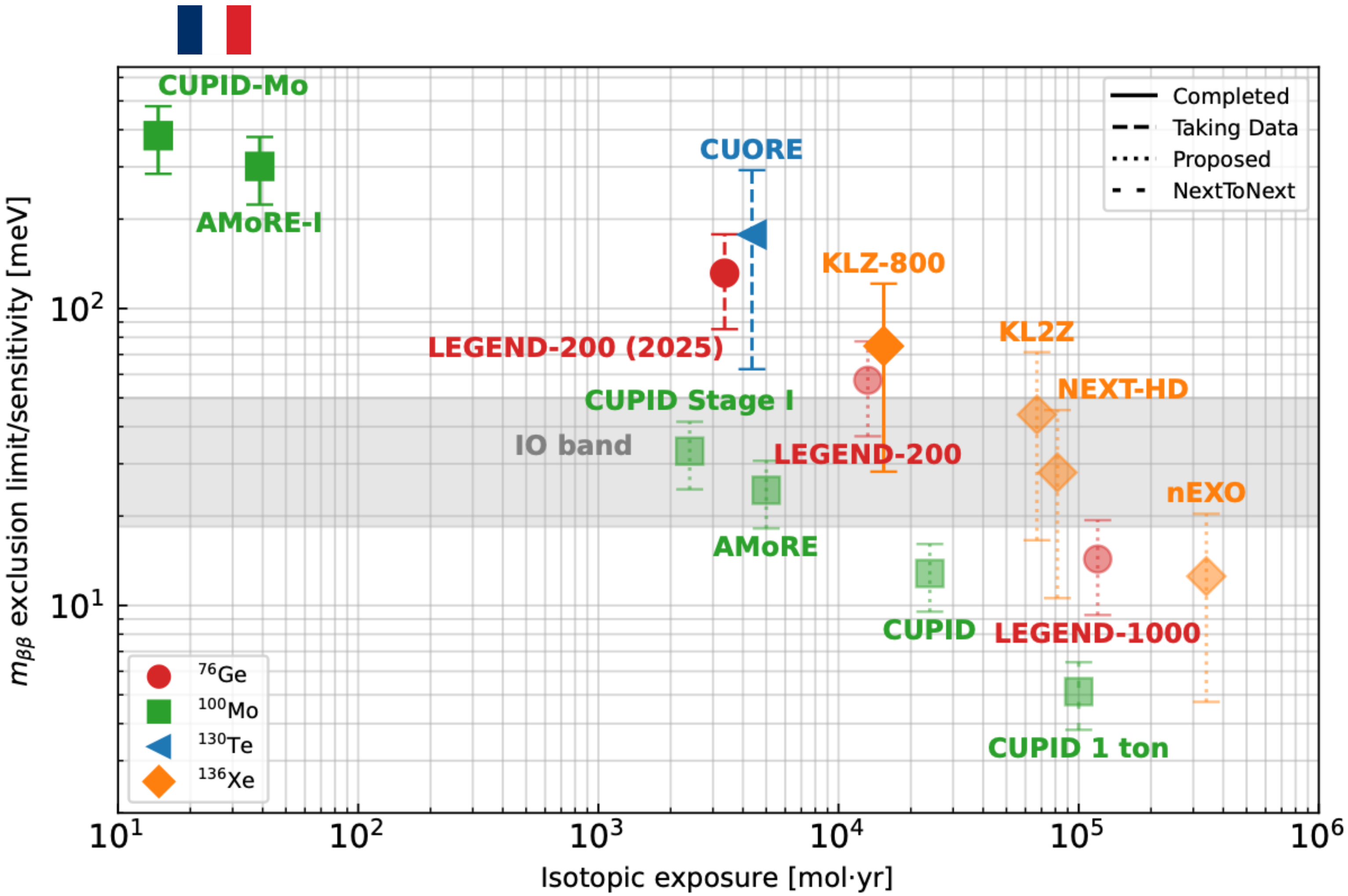
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} U_{e,i}^2 m_i \right|$$

- **^{100}Mo is very advantageous thanks to its combination of NME and phase space factor**

CUPID and current exclusion results



Exclusion sensitivity in the field

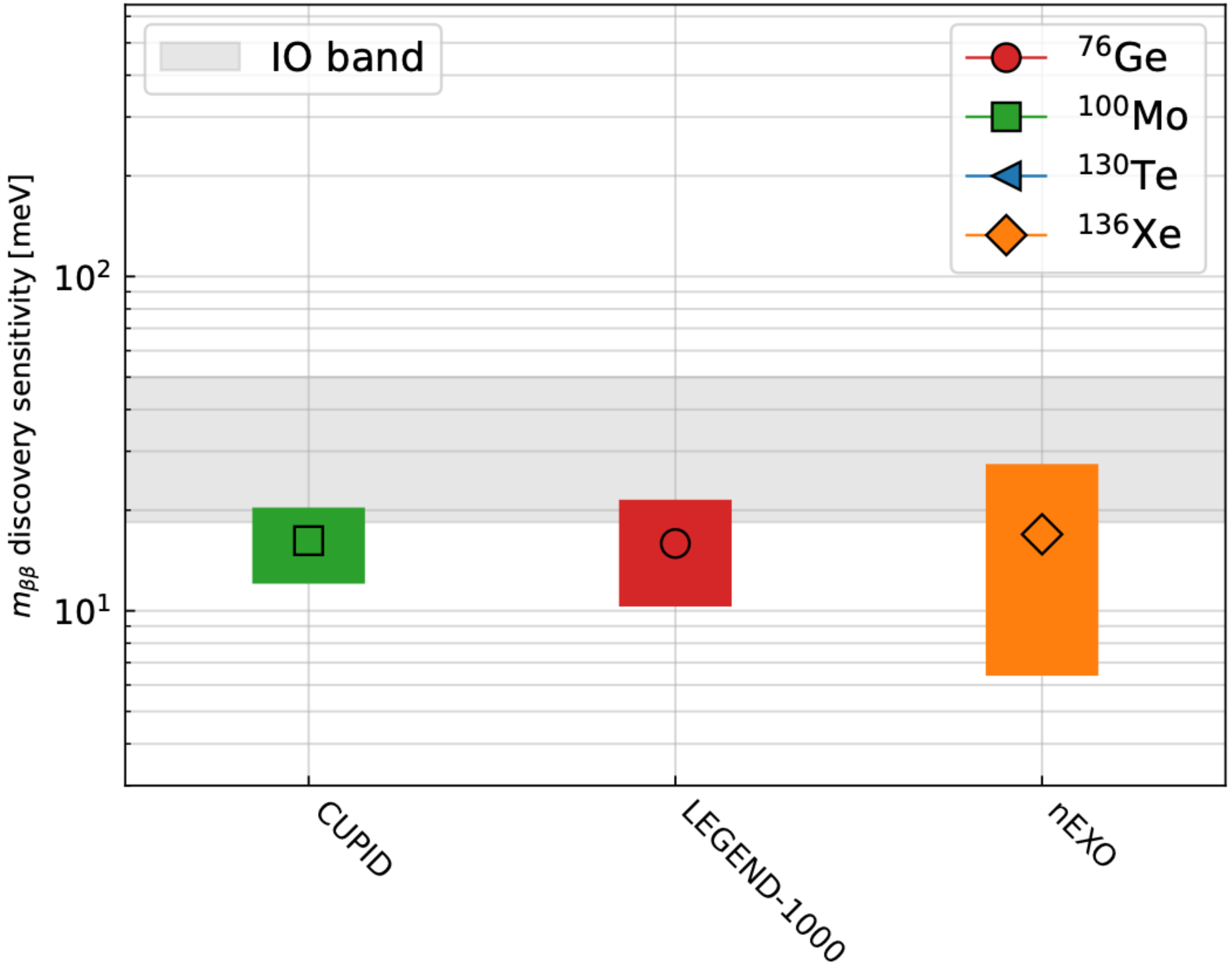


- **CUPID Stage I (3 yr)** arXiv:2504.14369
- Is on a similar sensitivity/timeline/trajectory as
  LEGEND-200 (5 yr), arxiv:2107.11462
  KL2Z (10 yr), Rev. Mod. Phys., Vol. 95, No. 025002
  NEXT-HD (10 yr), arxiv:2005.06467
  AMoRE-II (5.2 yrs) 2nd phase, EPJC 85,9

CUPID's and CUPID "France" strength

- Cost-effective
- More sensitive than LEGEND-200 (5 yr)
- More advanced/mature compared to AMoRE - Existing infrastructure, background model, operational & analysis experience
- A discovery type experiment with a clear peak signature
- French leadership in the technology development for CUPID and crucial role in simulation and sensitivity estimates

Discovery sensitivity - Stage II



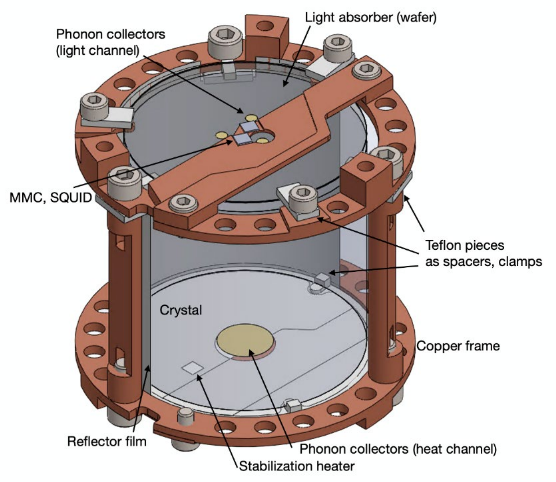
- **CUPID Stage II (10 yr)** Eur. Phys. J. C 85, 737 (2025)
- Is on a similar sensitivity/timeline as LEGEND-1000 (10 yr), arxiv:2107.11462 nEXO (10 yr), J. Phys. G: Nucl. Part. Phys. 49 015104
-

CUPID's and CUPID "France" strength

- Cost-effective
- Mature: Existing infrastructure & experience, Robust predictions for background improvements of x 30 compared to CUPID-Mo
- Significant remaining potential for technological improvement
- Discovery type experiment based on technology developed in France

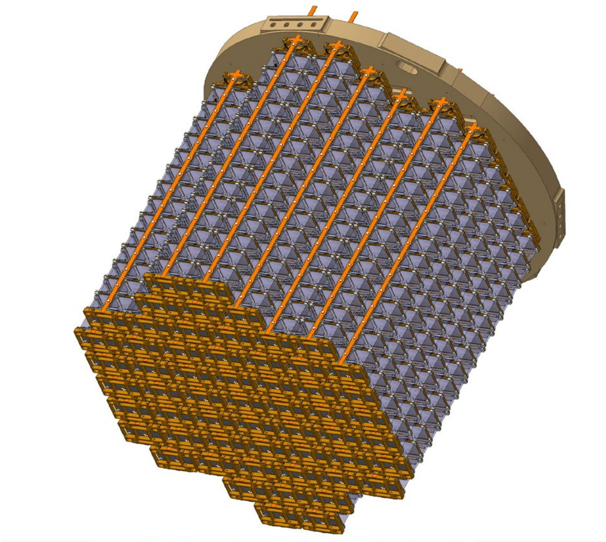
AMoRE | CUPID | CUPID-China
(The ^{100}Mo landscape)

Long term community goal: International, collaborative effort at the tonne-scale, with CUPID-style experiments distributed at multiple sites around the world



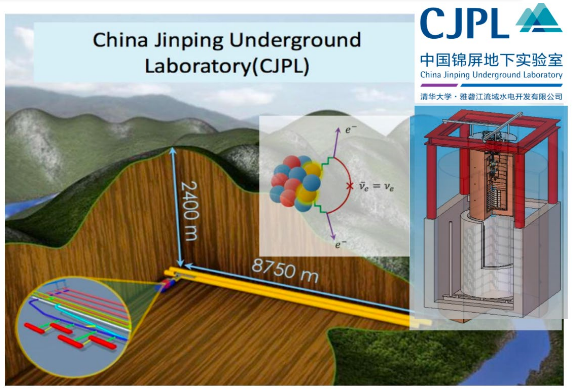
AMoRE-II (100 kg ^{100}Mo)
Different technology (MMC) faster

Needs to demonstrate a background reduction by a factor ~250 from AMoRE-I
2.5 x 10^{-2} ckky to 10^{-4} ckky



CUPID (240 kg ^{100}Mo):
Mature & low risk

Builds on CUORE legacy and proven technology and experience



CUPID-China: Partially part of CUPID in particular implicated in crystal production for CUPID

Goals: Short to Mid-term Demonstrator type experiment at CJPL (O 10 kg) Crystal production coordinated with CUPID

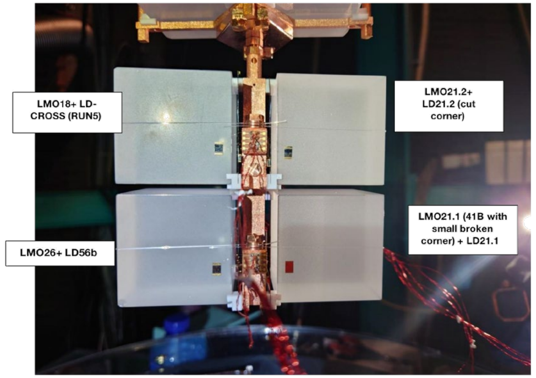
Long-term ambition to contribute a CJPL-based experimental site for tonne-scale ^{100}Mo experiment

Long term perspectives - R&D status

Goal: Distributed international tonne-scale or multi tonne-scale experiment with ^{100}Mo or ^{130}Te:

Economically possible
Requires background reduction by O(10) for ^{100}Mo, by O(1000) for ^{130}Te
R&D well on its way!

Many ideas and strong visibility in France:



Significant further suppression of radiogenic bg possible

Bolometers with surface sensitivity JHEP 2020, 18 (2020)
Novel assembly & active veto NIM A 1069, 169936 (2024)
New isotopes (TINY ERC)

- and elsewhere:
  - LD with fast sensors (MMC, TES, KID)
    - MMC: AMoRE EPJ-C 85, 172 (2025)
    - TES: Phys. Rev. Applied 20, 064017 (2023)
    - KID: EPJ-C 79, 724 (2019)
  - Next up: Neganov-Trofimov-Luke assisted Light Detectors + fast sensors (MMC, TES)
  - Faster sensors on LMO (MMC, TES, KID)
    - Potential for extra position/topology information (Opossum ERC)
    - TES: EPJ-C 85,118 (2025) - French involvement
    - MMC: AMoRE (EPJ-C 85, 172 (2025))
  - Multiplexing: arXiv2509.07223
  - New active holder materials EPJ-P 138, 384 (2023)