见微学术沙龙
USTC Jianwei Seminar

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The bolometric way to neutrinoless double beta decay: CUPID, CROSS and BINGO

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Double beta decay

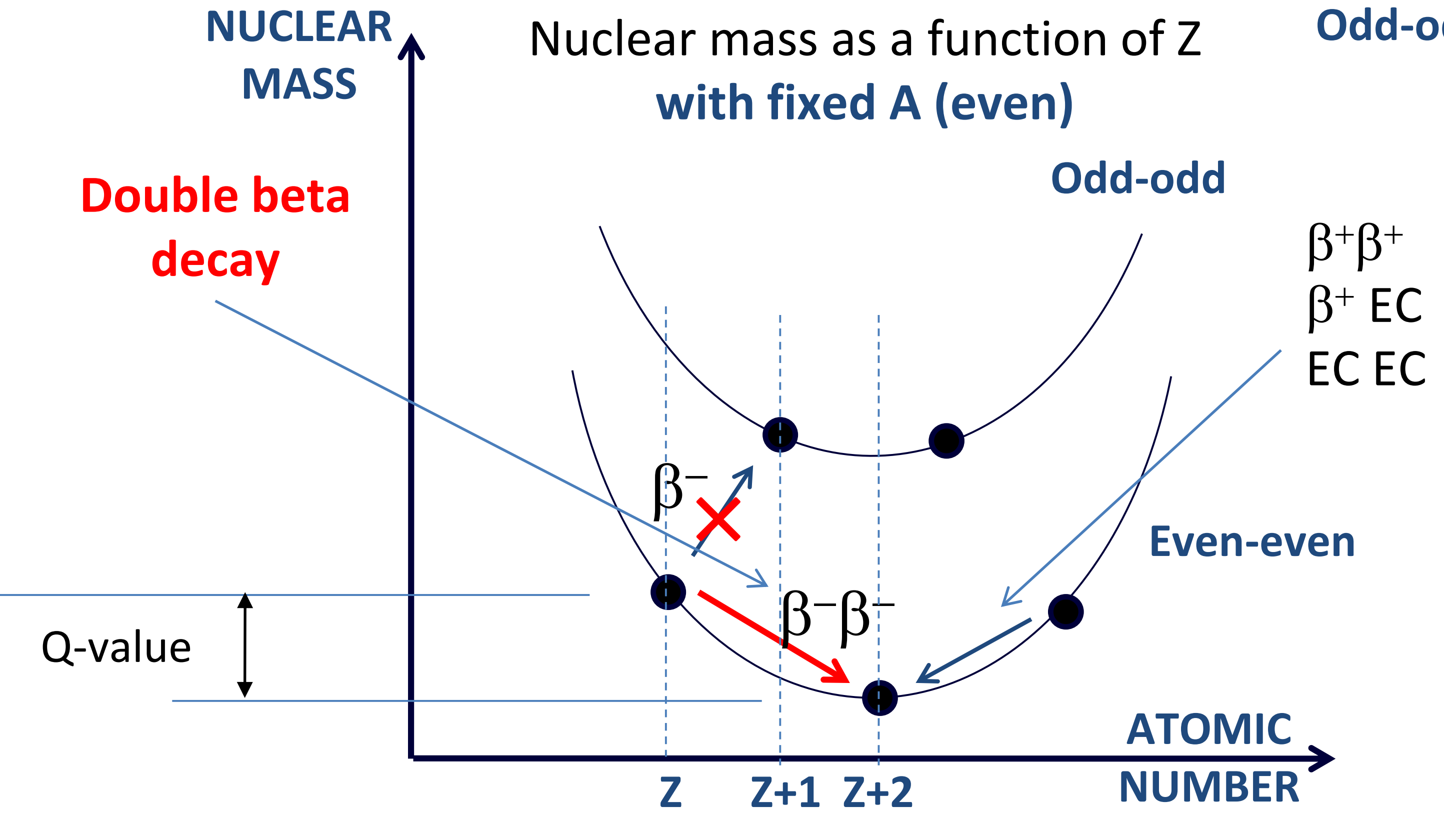
Very rare nuclear transition: (A,Z) $\rightarrow$ (A,Z+2) + 2e$^-$ +2ν_e

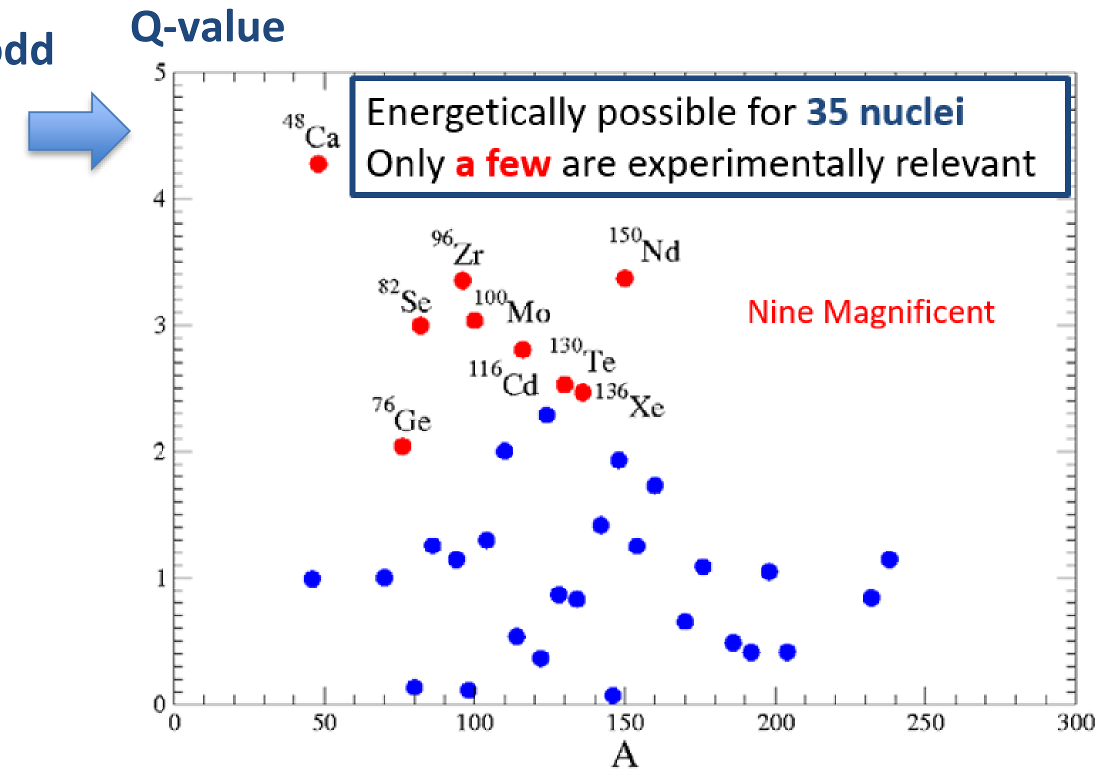
Weiszaecker's formula for the binding energy of a nucleus

Even-even

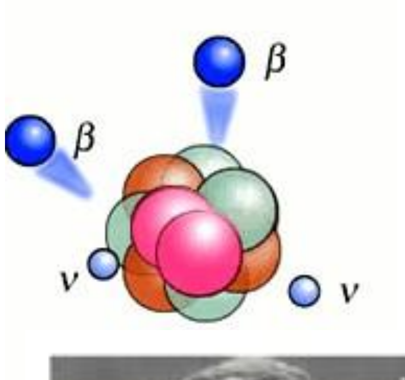
$$E_B(\mathrm{MeV}) = a_v A - a_a (N-Z)^2/A - a_c Z^2/A^{1/3} - a_s A^{2/3} \pm a_\delta/A^{3/4}$$

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 → $\mathbf{T_{1/2} \sim 10^{18} – 10^{24}}$ **y**

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

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

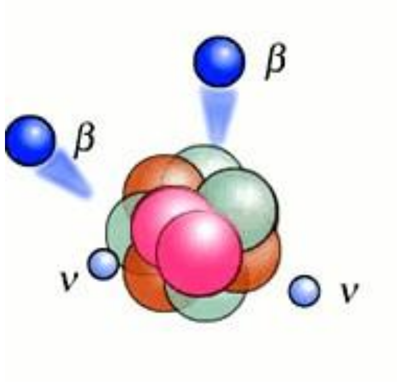
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

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



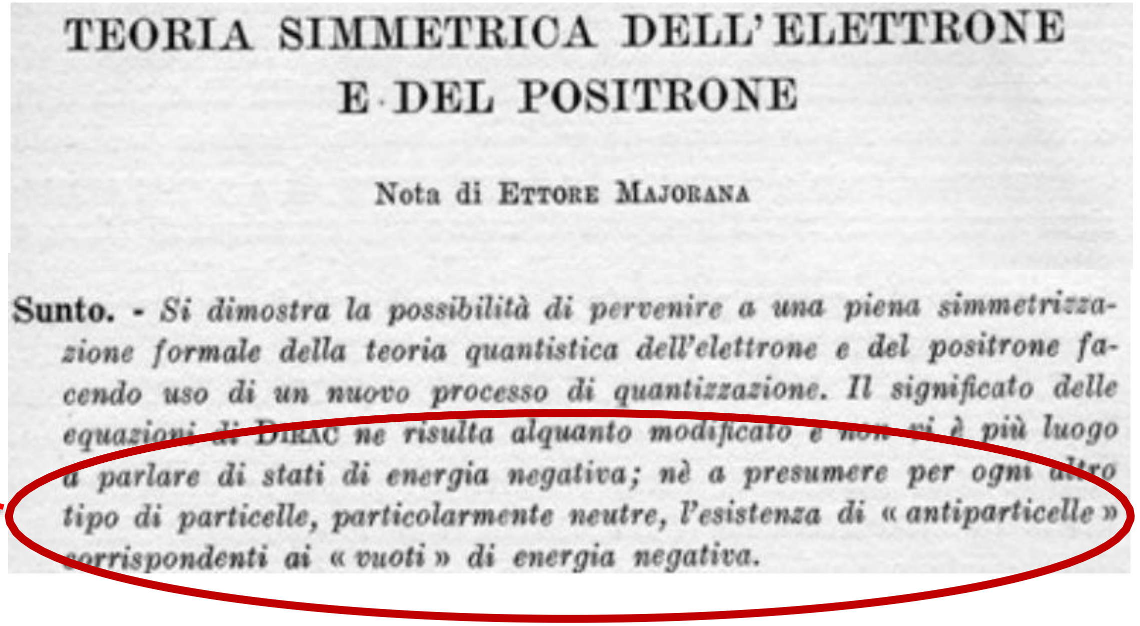
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \qquad 2\nu2\beta$$

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

Nuovo Cimento 14(1937)171-184

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

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

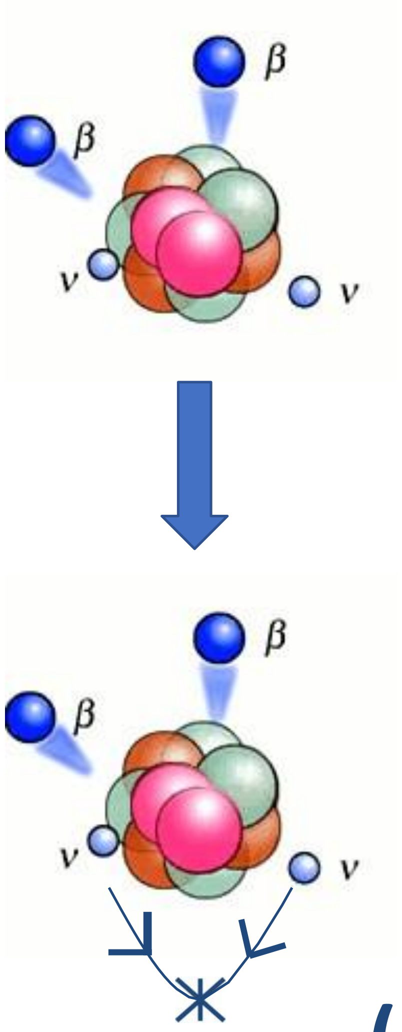


TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

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

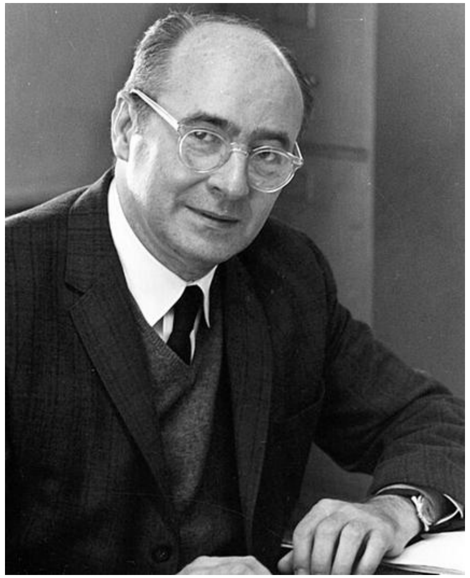


$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ $2\nu2\beta$

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

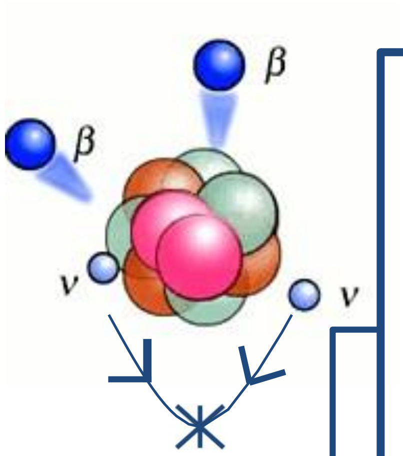
The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (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

$\Delta L = 2$

$0\nu2\beta$: the mechanisms

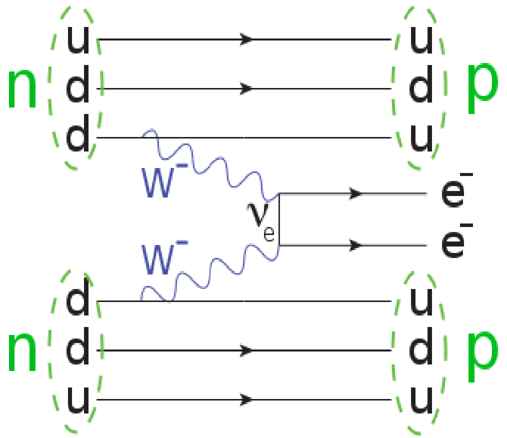


Minimal straightforward extension of the Standard Model to accommodate neutrino masses

Mass mechanism

$0\nu2\beta$ is mediated by
light massive Majorana neutrinos
(exactly those which oscillate)

Metric to compare experiments and technologies



Two key formulae

$0\nu2\beta$ decay rate

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

Effective Majorana neutrino mass

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

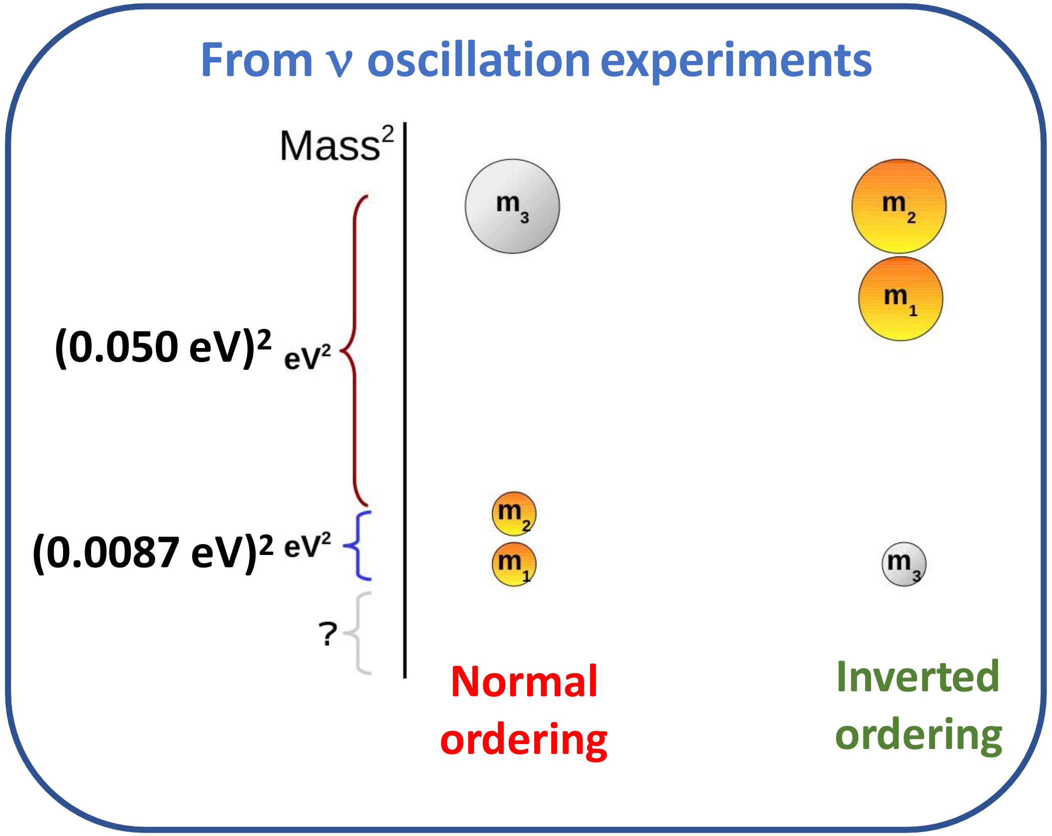
Connection with ν oscillation experiments

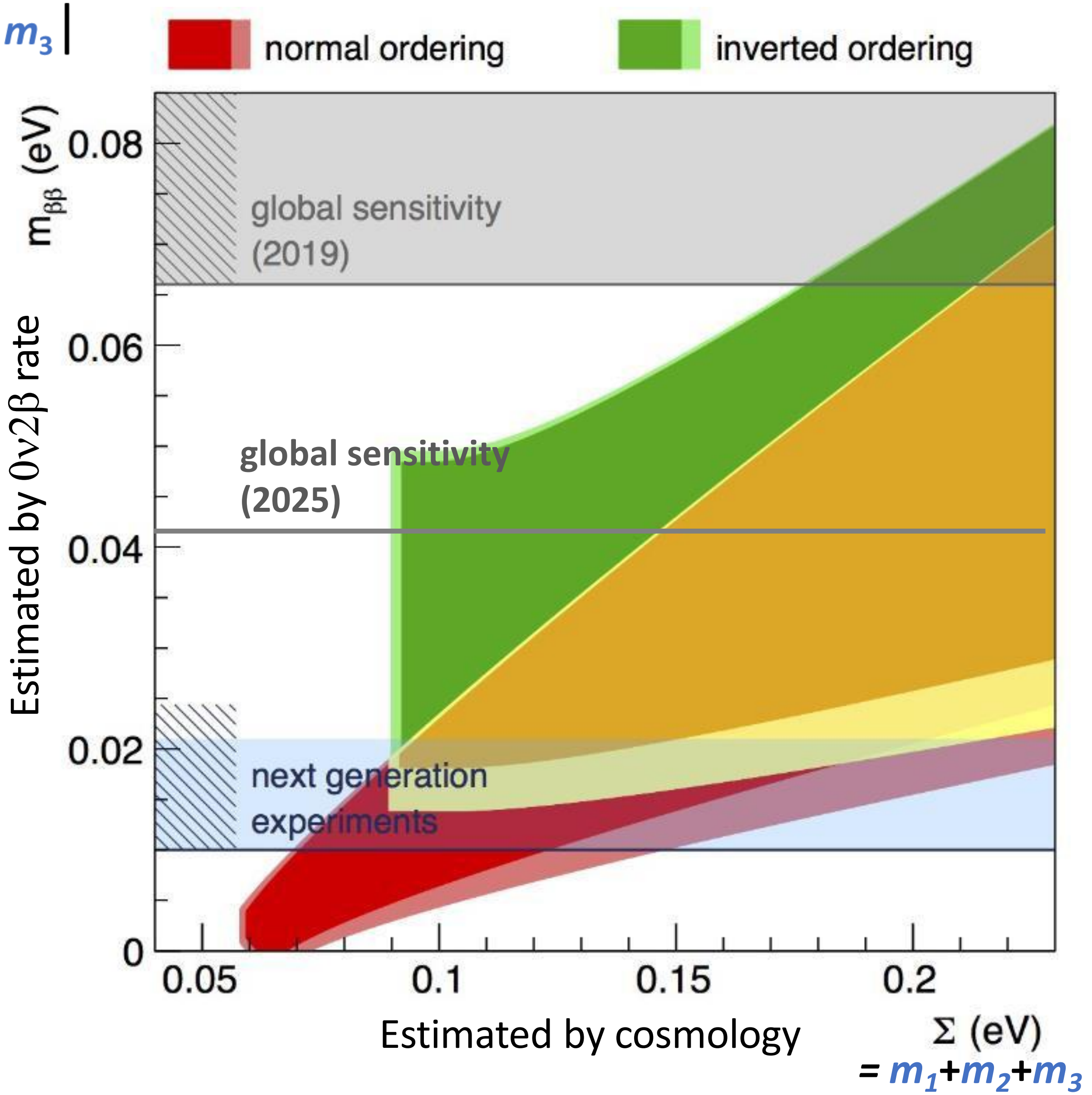
A pletora of other more exotic mechanisms:
Sterile ν, Right currents (W_R), SUSY,…

Not necessarily neutrino physics

Light Majorana neutrino exchange: the neutrino mass pattern

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





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**

Light Majorana neutrino exchange: the rate formula

how **0ν-DBD** is connected to **neutrino mixing matrix** and **masses**
in case of process induced by light ν exchange (**mass mechanism**)

Neutrinoless Double Beta Decay **rate**

Phase Space (calculable)

Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

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

what the experimentalists try to measure

what the nuclear theorists try to calculate

parameter containing neutrino physics:
Effective Majorana mass

Masses appear to accommodate helicities

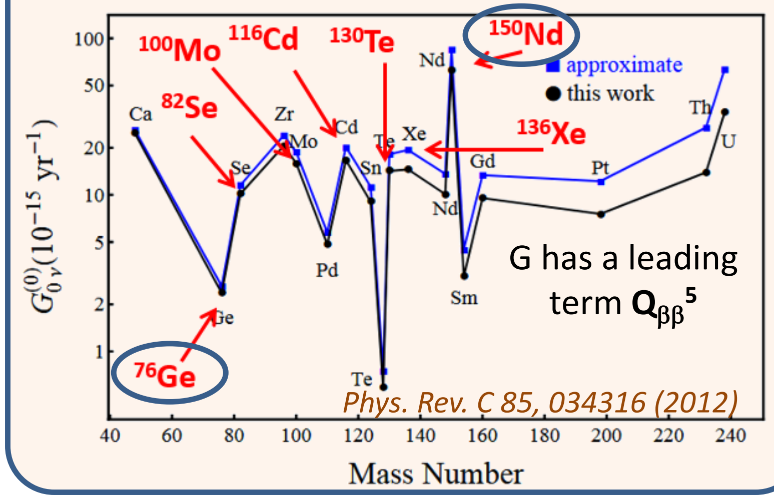
$$\mathbf{m}_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

α_i
Majorana phases

Light Majorana neutrino exchange: the rate formula

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

Phase space: exactly calculable

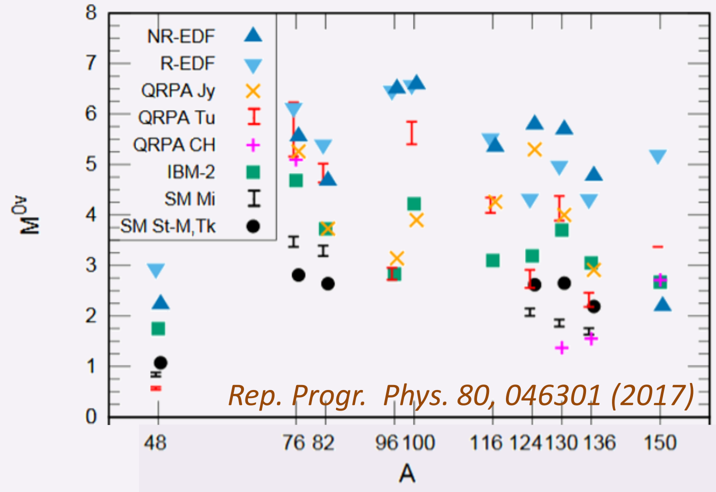


$g_A = \begin{cases} 1.269 & \text{Free nucleon} \\ 1 & \text{Quark} \end{cases}$

$g_{A,eff}$ ~ **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

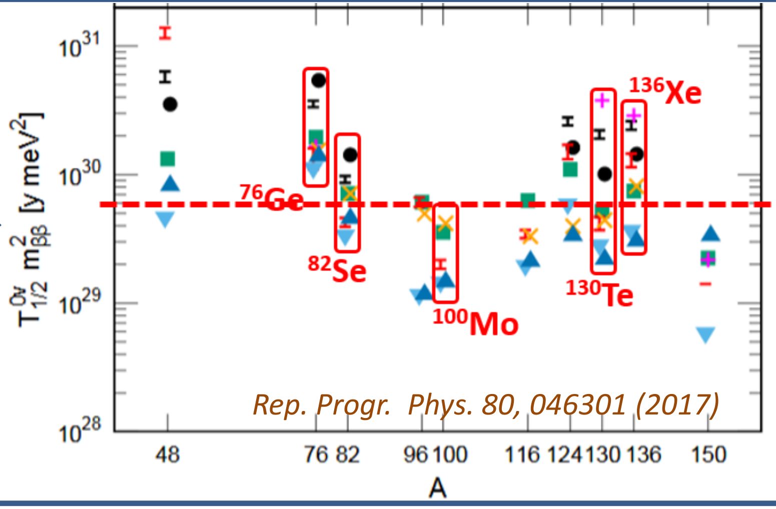


0νββ rate

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

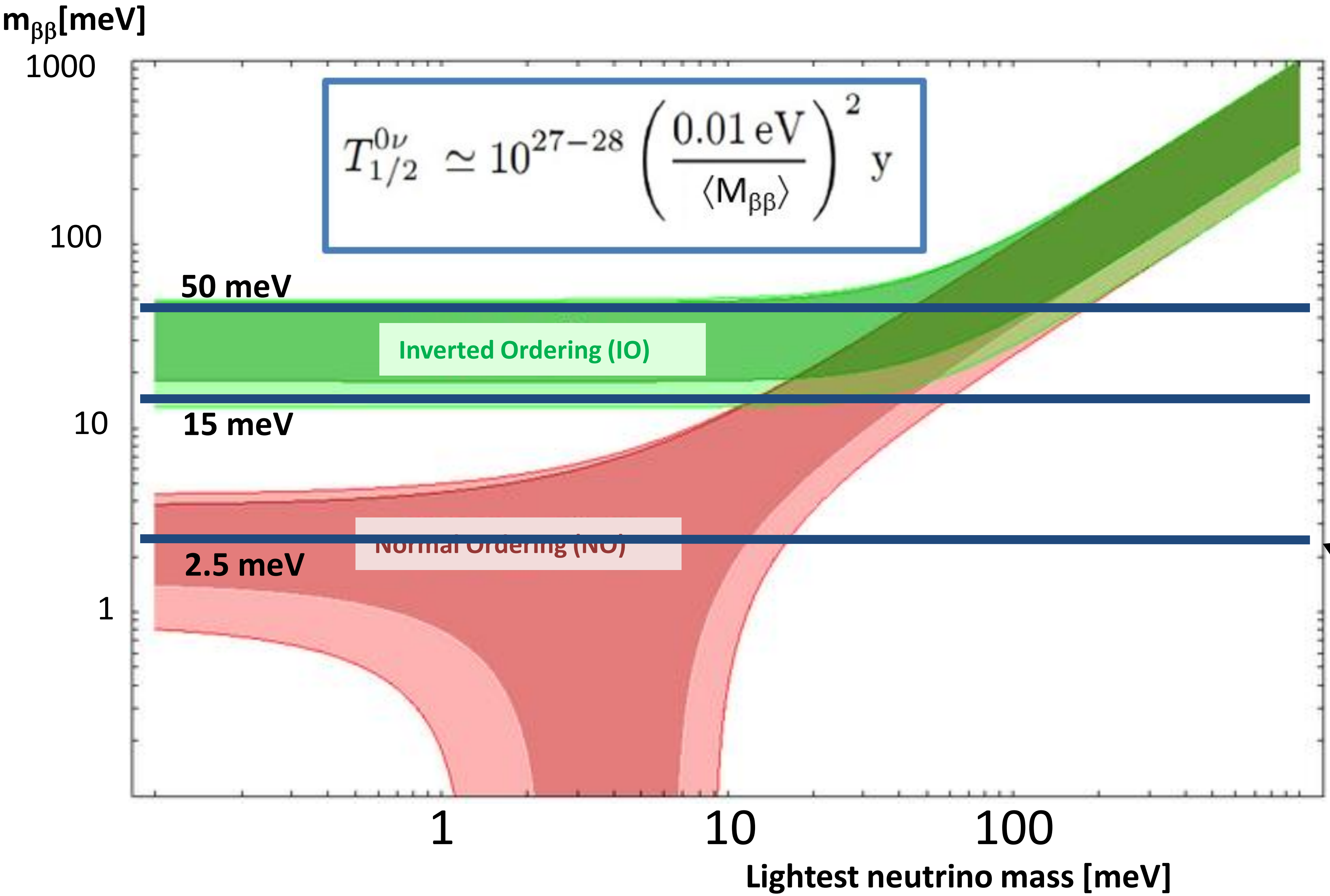
arXiv:2108.11805



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

Working formula for general experiment design

The experimental challenge

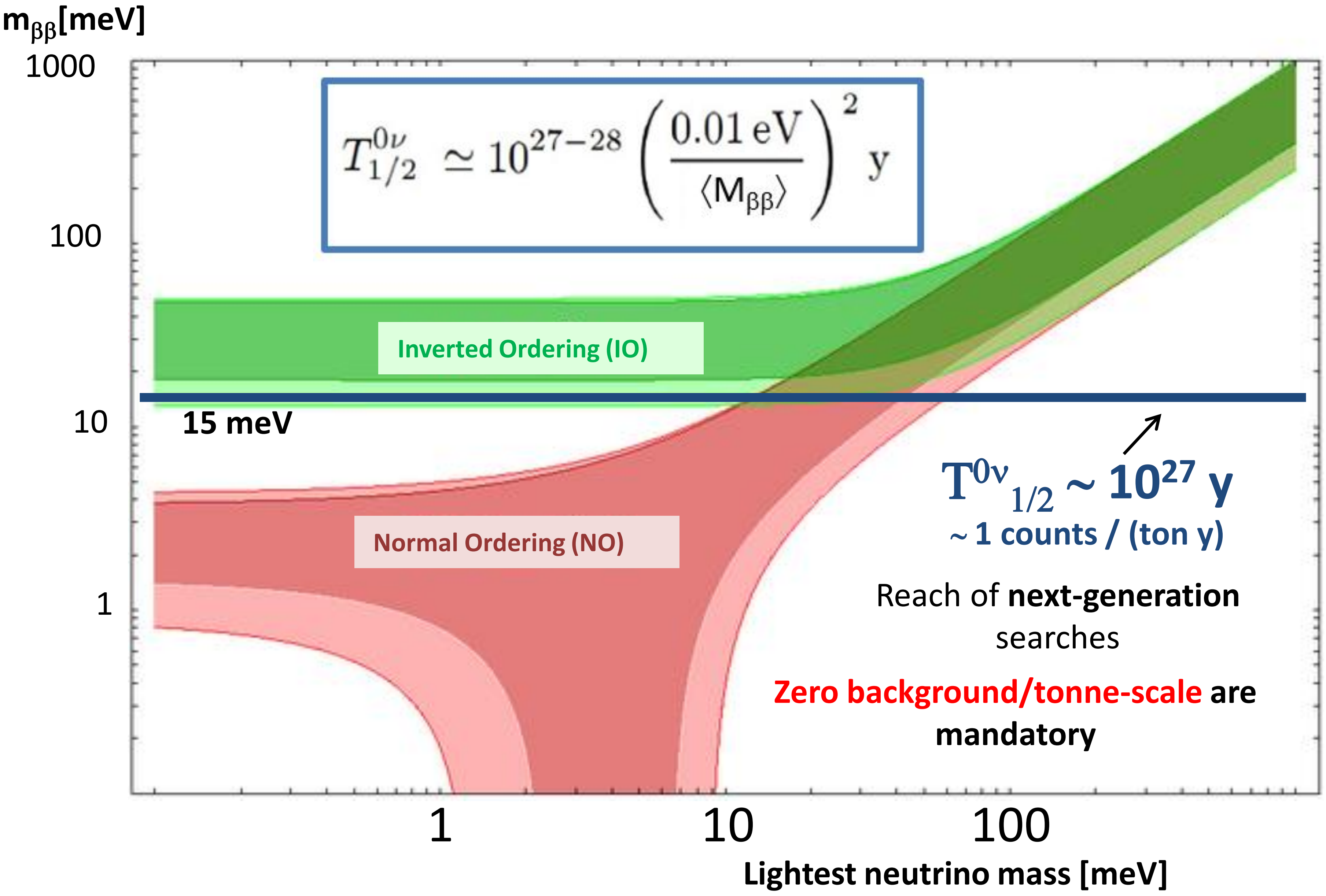


$T^{0\nu}_{1/2} \sim 10^{26}$ y
~ 10 counts / (ton y)
Reach of the **current** searches

$T^{0\nu}_{1/2} \sim 10^{27}$ 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

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

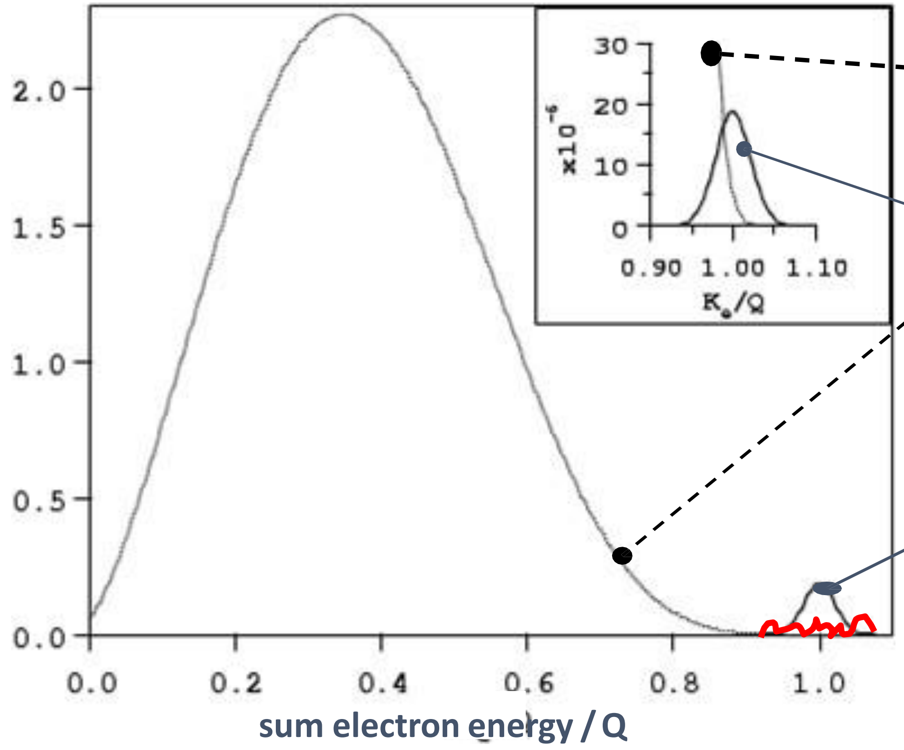
Zero background

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

$F \propto MT$

Searching for 0ν2β

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



2νββ: (A,Z)→(A,Z+2)+2e+2ν
Continuum with maximum at ~1/3 Q

0νββ: (A,Z)→(A,Z+2)+2e
Peak enlarged only by the detector energy resolution

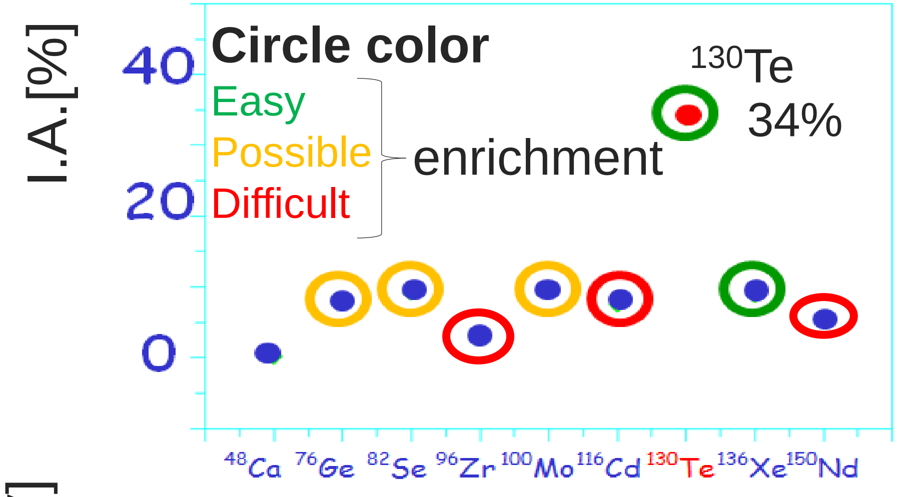
Backround index BI
counts/(keV kg y)

Q ~ 2-3 MeV for the most promising candidates

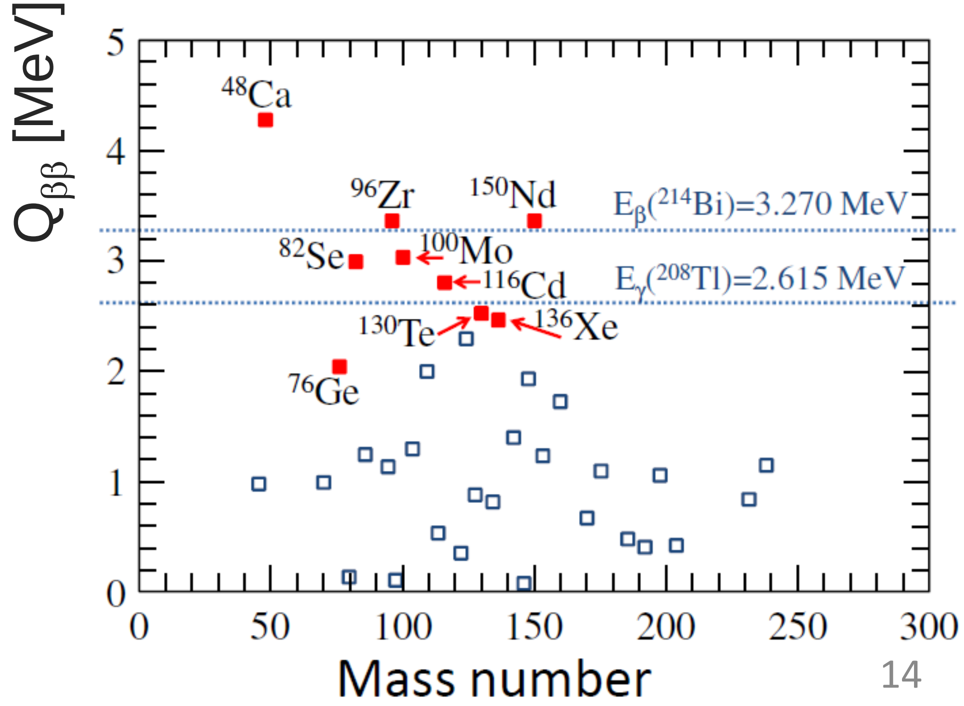
The signal is a **peak (at the Q-value)** over an almost flat **background**

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**

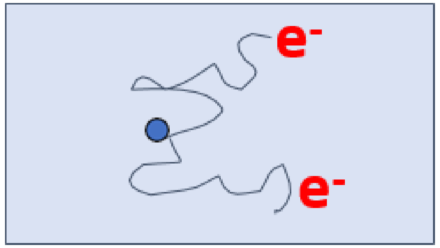
- **High energy resolution**
- **Background identification**
- **Efficiency and scalability**

Searching for $0\nu2\beta$

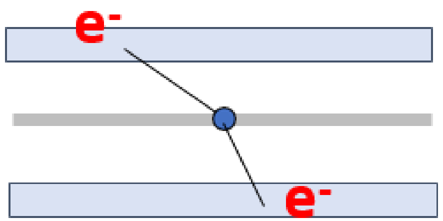
Requests for the source

① **Large source** $\rightarrow$ tonne scale $\rightarrow$ > 10^{27} nuclei

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



Source $\subseteq$ Detector



Source $\not\subseteq$ 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

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

Liquids and gases

② **TPCs**

EXO-200 – NEXT – nEXO (^{136}Xe)

→

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

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

Single crystals

Experimental status

Published results

KamLAND-Zen 800 - $T_{1/2} > 2.3\times10^{26}$ y
Phys. Rev. Lett. 130, 051801 (2023)

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)

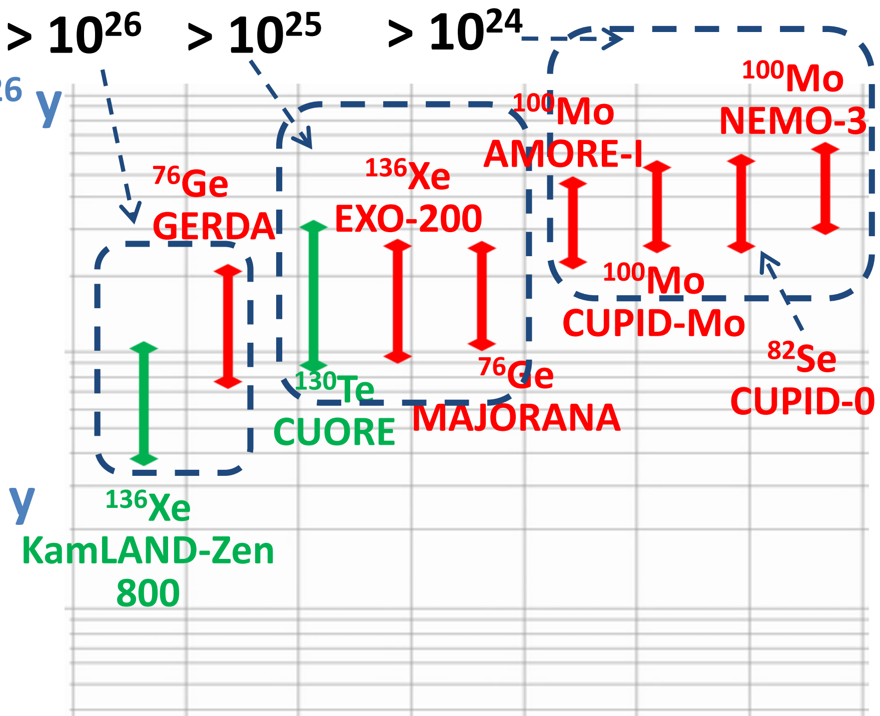
CUORE - $T_{1/2} > 2.2\times10^{25}$ y
Nature 604, 53-38 (2022)

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)

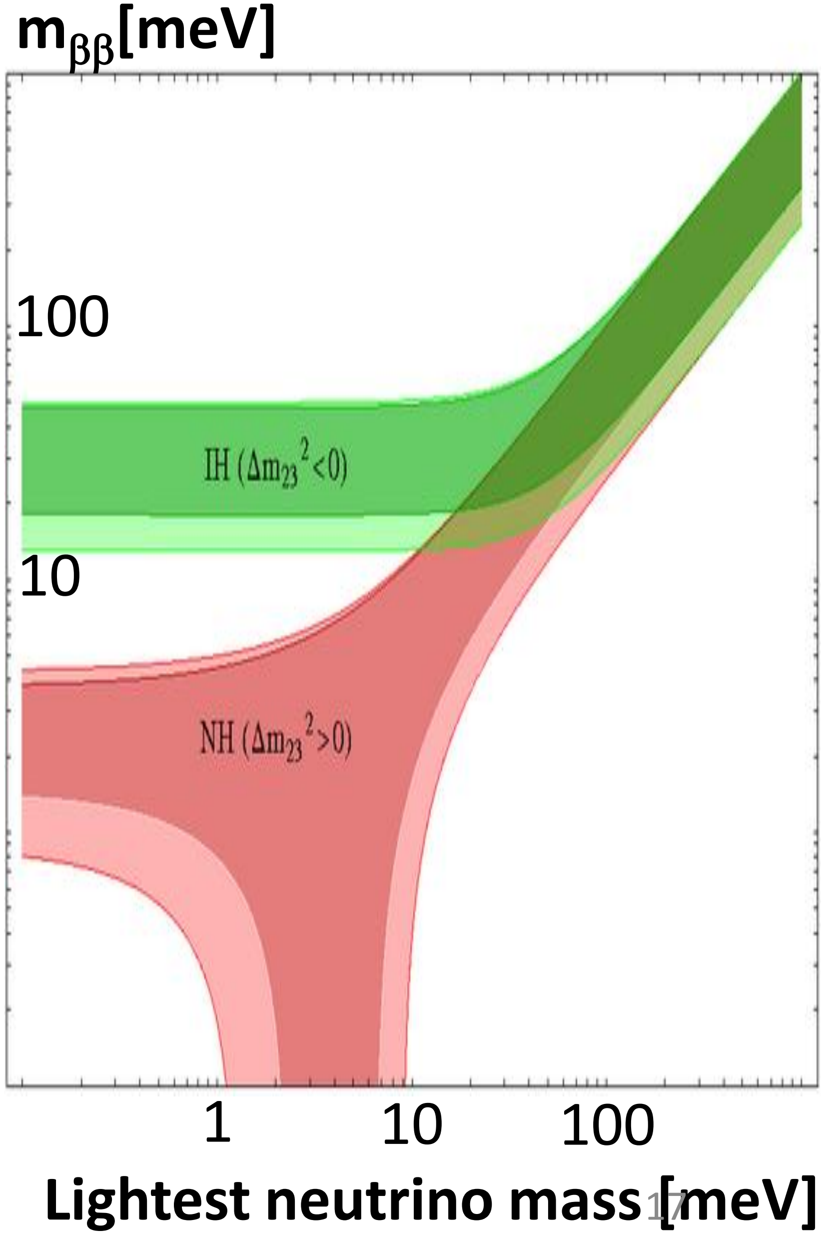
NEMO-3 - $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)



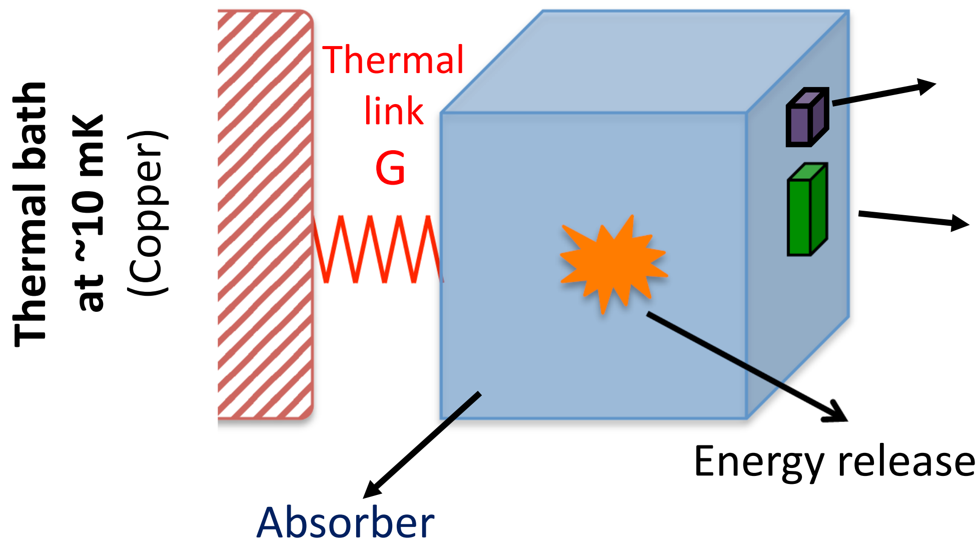
$T_{1/2} > 10^{24}$ y 90% C.I. restricted club

All experiments stopped except **KamLAMD-Zen 800** and **CUORE**

(bolometric searches are underlined)

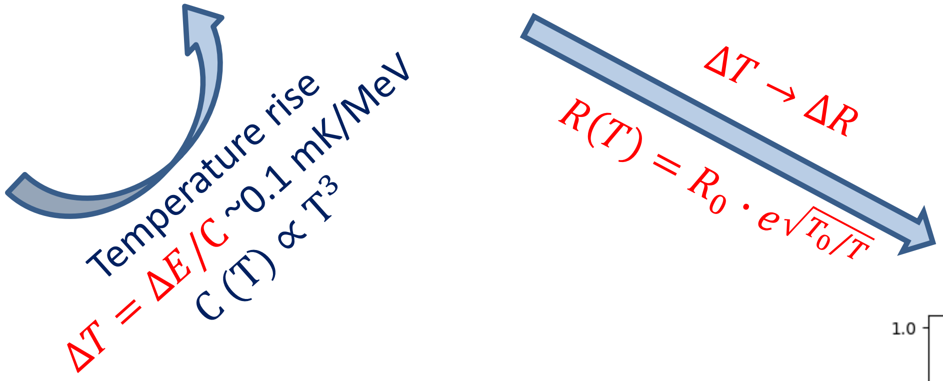


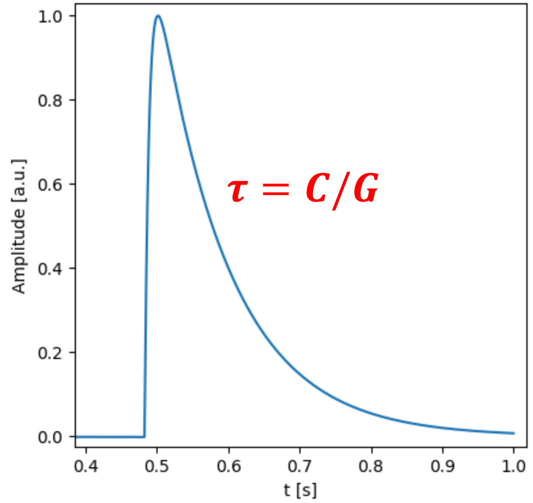
Bolometric technique



Heater:
For correction of temperature instabilities

Temperature sensor:
Neutron Transmutation Doped (NTD) Germanium thermistor





Bolometric detector properties match well the required features for $0\nu2\beta$ search

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

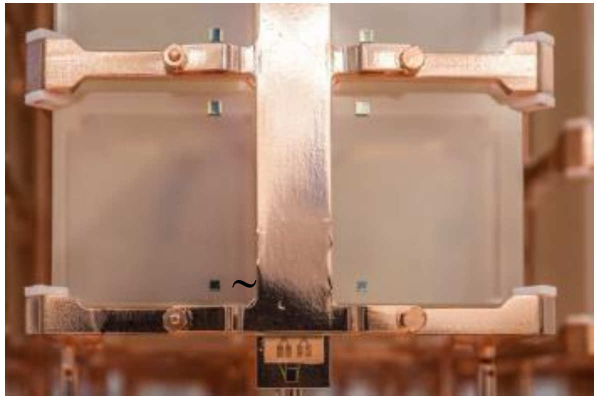
CUORE in a nutshell

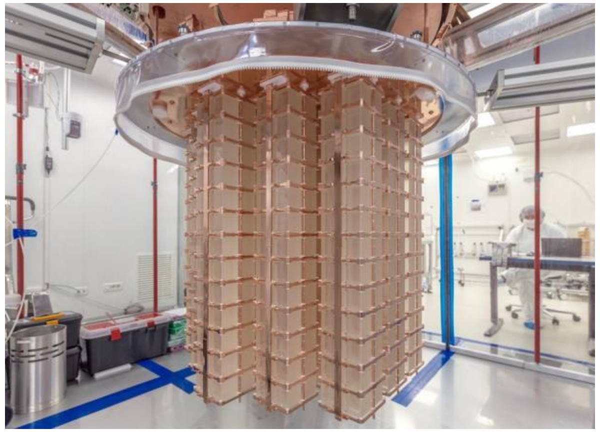
CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy) at **~12-15 mK**

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**)
- Background according to expectations **BI = 1.49(4)×10^{-2} counts/(keV·kg·y)**
- Energy resolution (at 2615 keV) close to expectations: **7.78(3) keV FHWM**

Nature 604, 53-38 (2022)

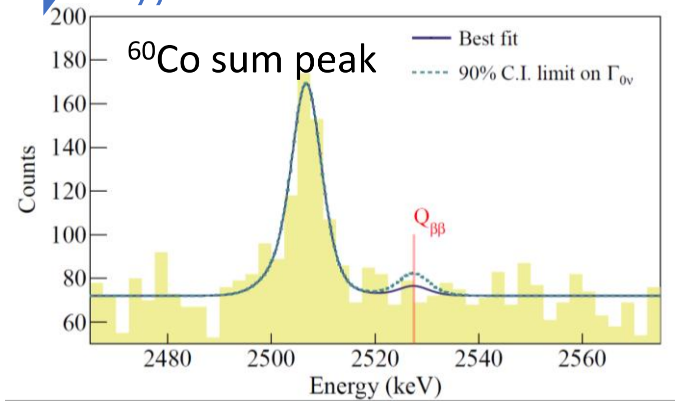




One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Analyzed exposure: **2039.0 kg·y** (567.0 kg·y ^{130}Te)
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 3.8 × 10^{25} y**

→ **$m_{\beta\beta}$ < 70 – 240 meV**



CUORE is not background free

→ ~**50 counts/y in the ROI**, dominated by **surface alpha background**

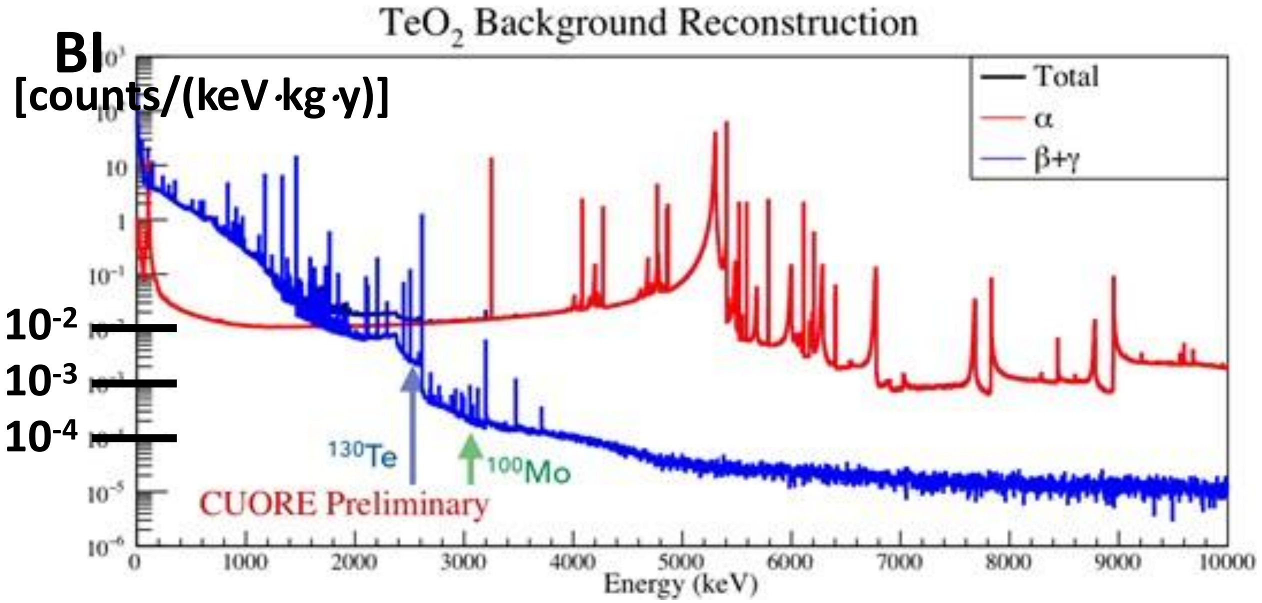
CUORE → CUPID

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 (~2024)

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

CUORE background model

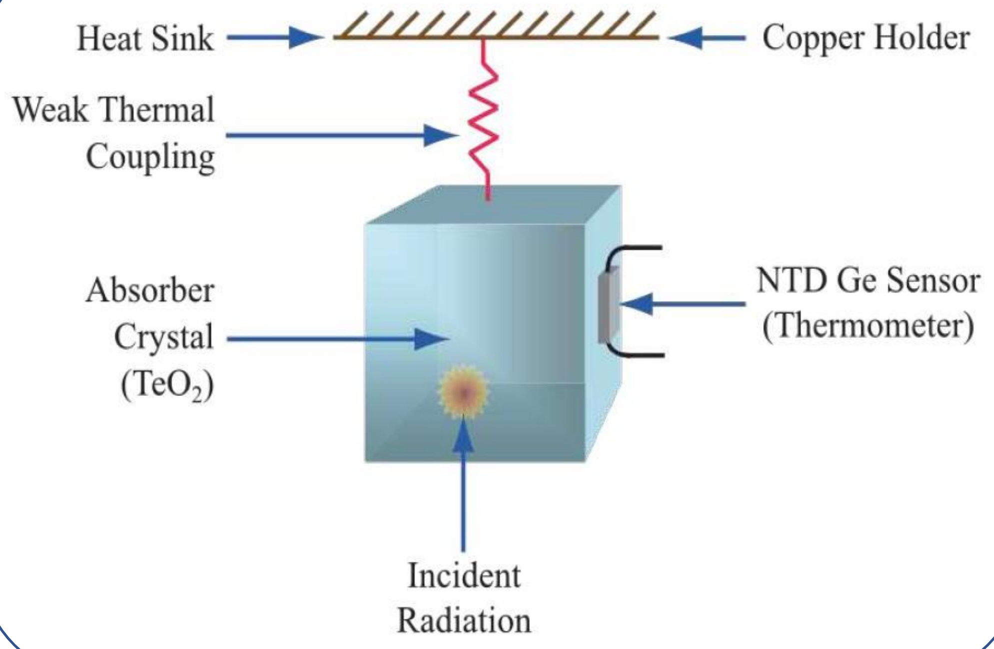


- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**

  → $Q_{2\beta}$: 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**)

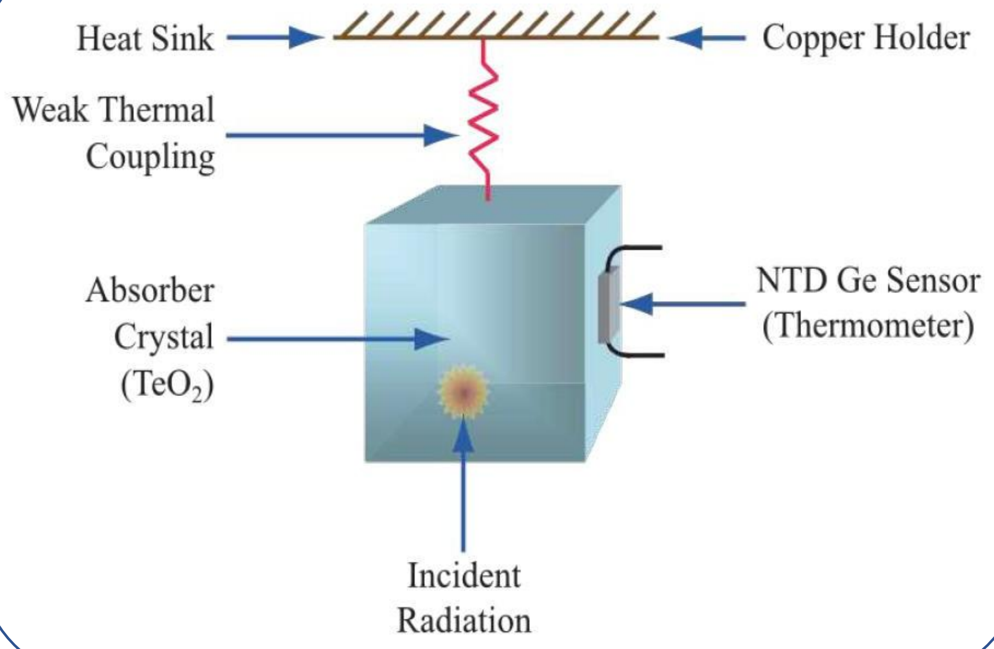


No PID

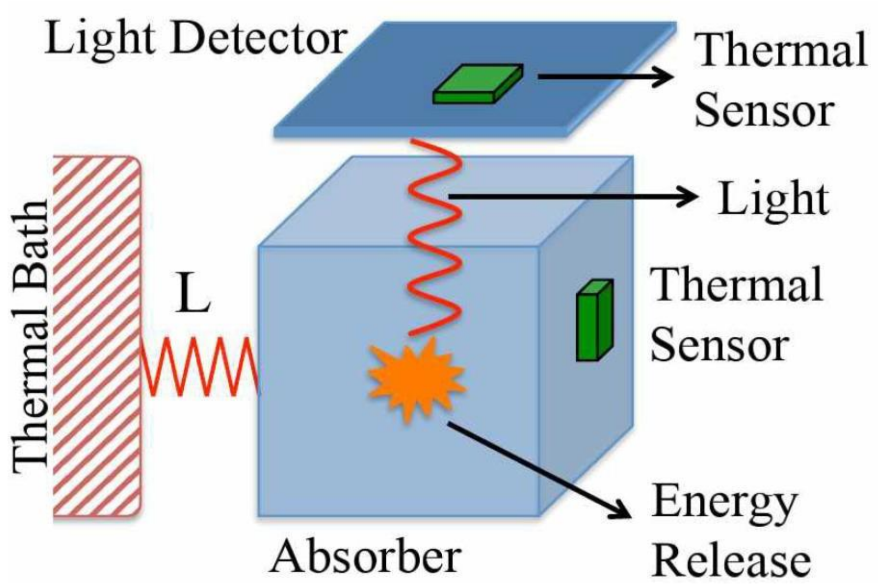
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

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

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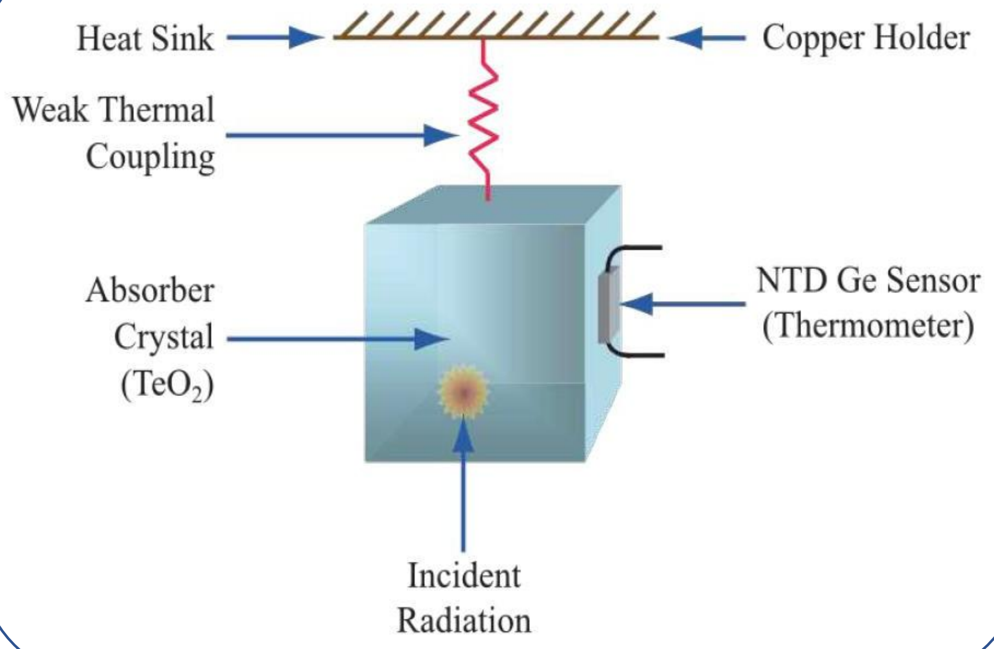

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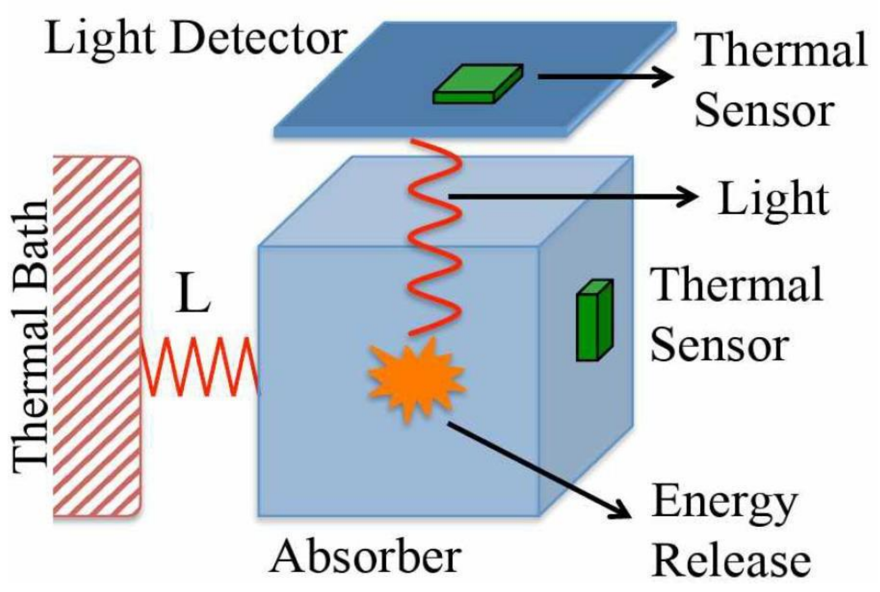
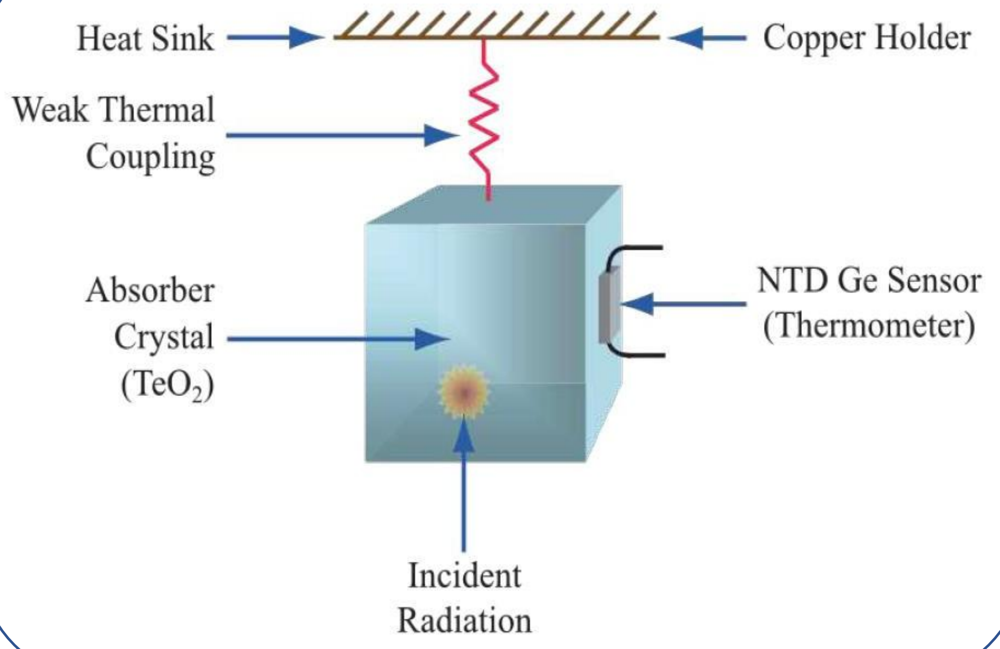


No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

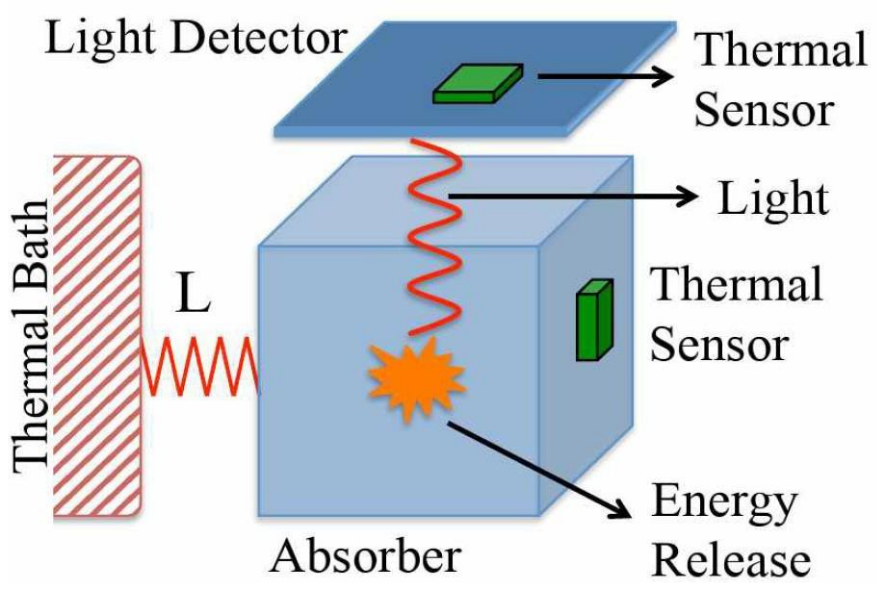
~~α background~~ ← **PID**
γ background

CUPID rationale

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



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

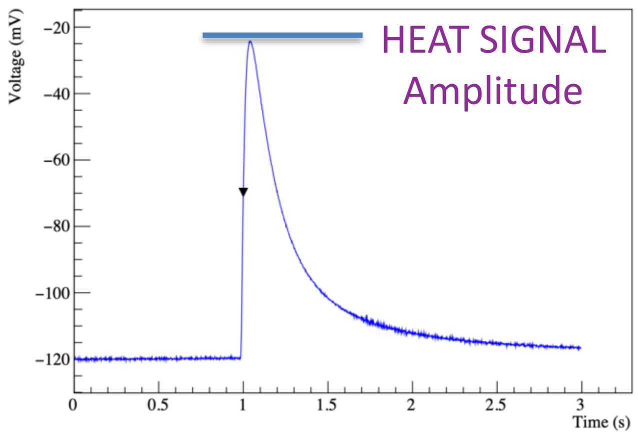


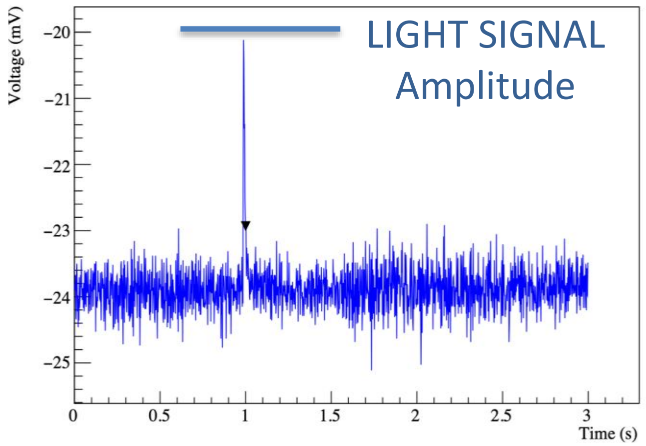
No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

~~α background~~
~~γ background~~

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

Coincidences between heat and light signals



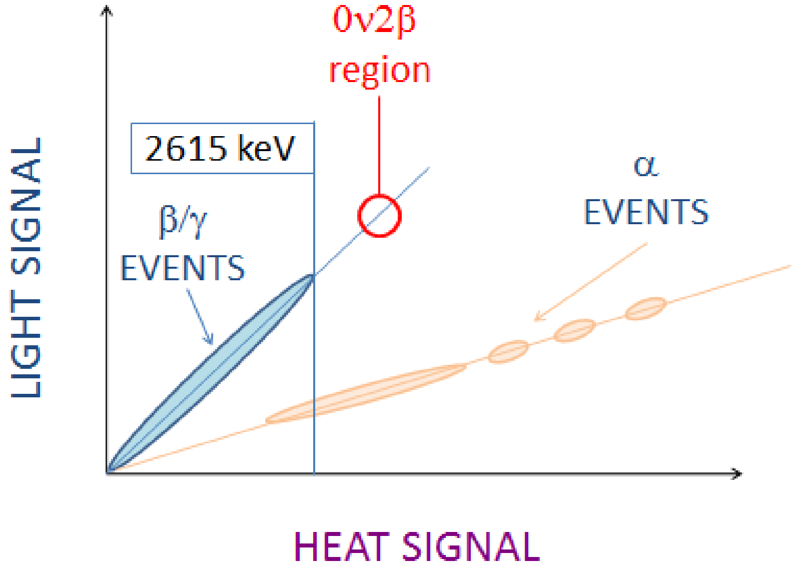


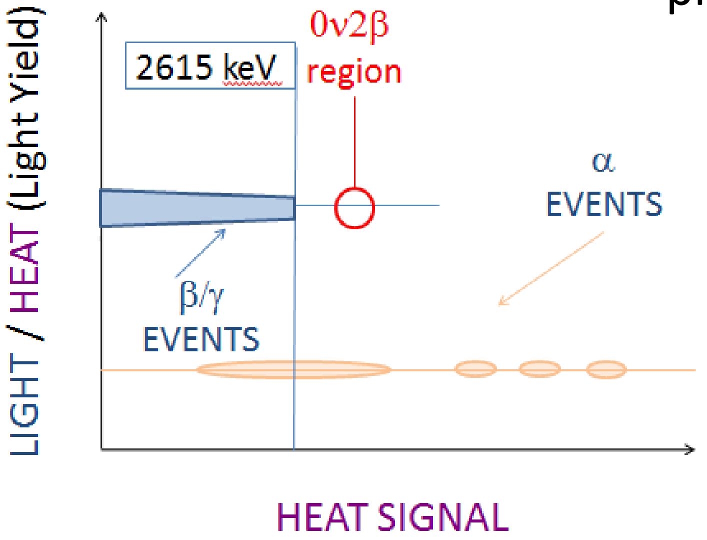
TIME [s]

Actual heat-light coincidence in the CUPID-Mo experiment

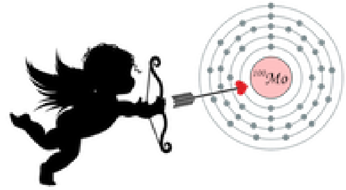
Same time scale!

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



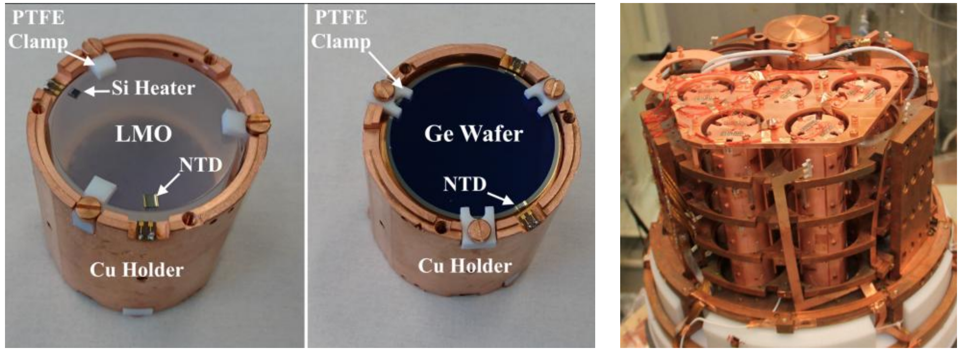


CUPID-Mo



CUPID-Mo experiment

- 20 scintillating bolometers arranged in 5 towerscrystal (~ 97% enrichment level) and 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
- ~ 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

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

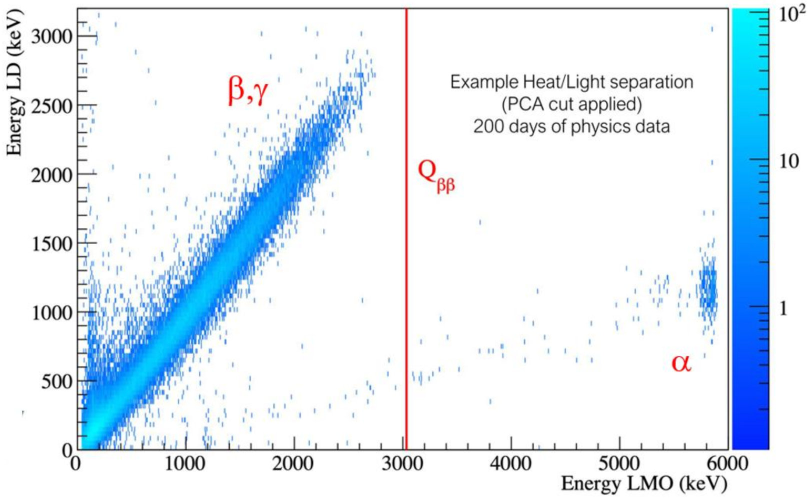
Energy resolution (FWHM)

6.6 ± 0.1 keV @ 2615 keV

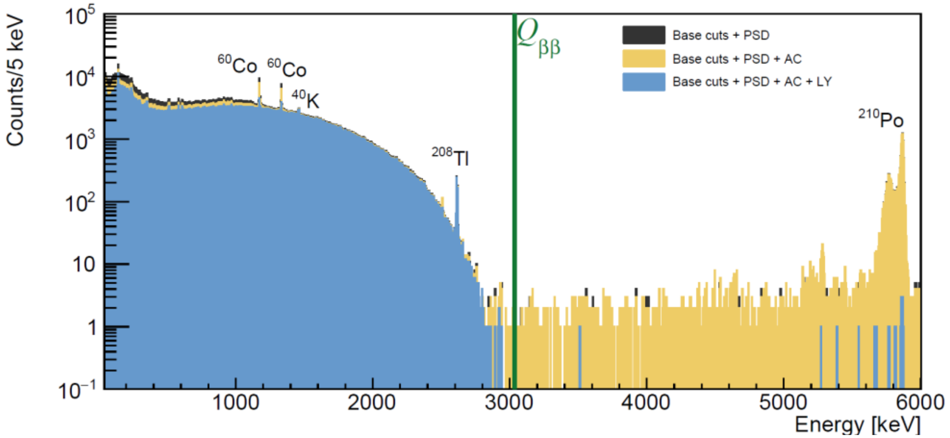
7.4 ± 0.4 keV @ $Q_{\beta\beta}$ (3034 keV)

Total BI:

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



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

CUPID structure

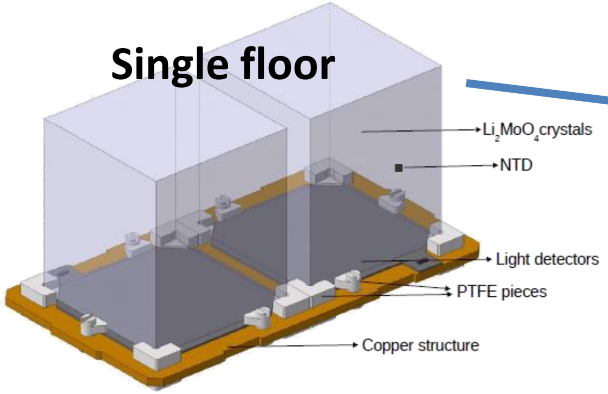
Eur. Phys. J. C 85, 737 (2025)

- Single crystal module: $Li_2{}^{100}MoO_4$ **45×45x45 mm** – **~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms

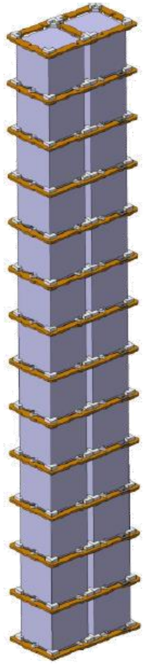
Baseline design

Gravity stacked structure

Single floor



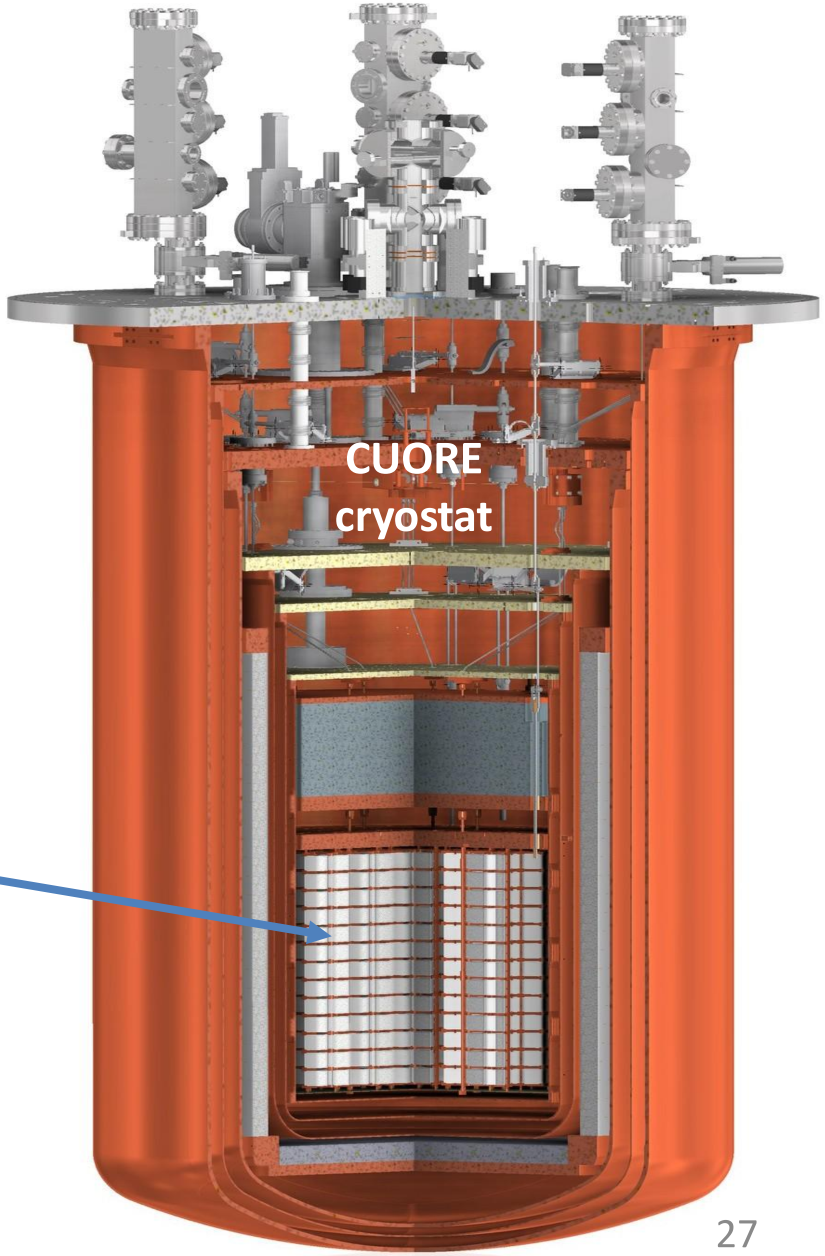
Single tower



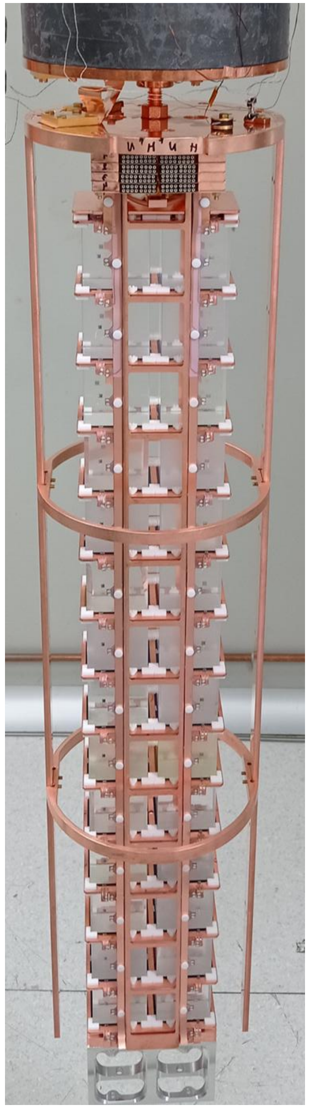
1710 Ge light detectors with SiO antireflective coating (each crystal has top and bottom LD)

- No reflective foil
- Exploitation of the Neganov-Trofimov-Luke effect

Muon veto and **neutron shield**



Test of a full CUPID tower at LNGS



BDPT

(baseline design prototype tower)

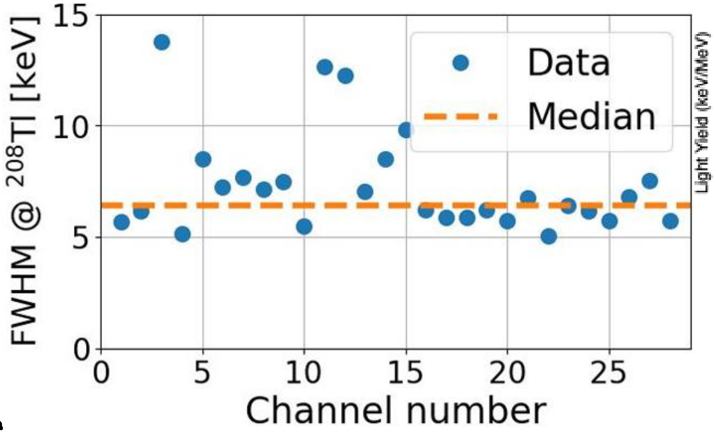
- 28 LMO crystals
- 30 Ge light detectors **without NTL**
- Tested at LNGS

Results:

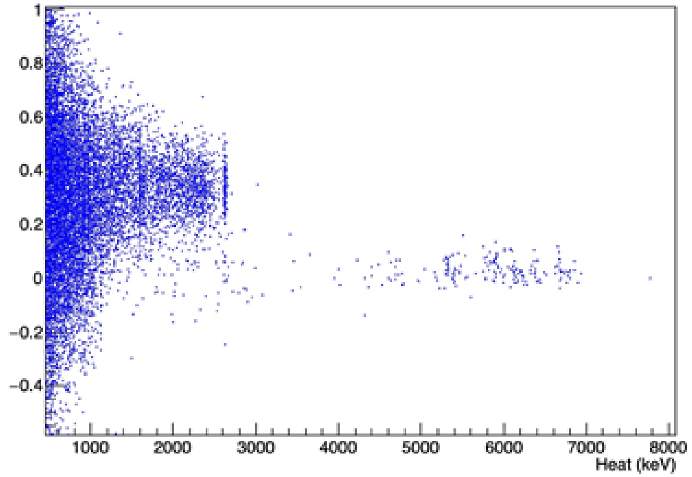
- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance:
  median $FWHM_{2615\ keV}$ = 6.2 keV
- median light yield: 0.34 keV/MeV
- α vs β, γ discrimination capability:

$$DP = \frac{|LY_{\beta,\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta,\gamma} + \sigma^2_{\alpha}}} = 3.21$$

- some excess noise on the LD -> changes to the LD assembly structure for the next test



Example of α/β separation in a low noise channel



Next test: VSTT (Vertical Slice Test Tower)

- A new test is currently ongoing

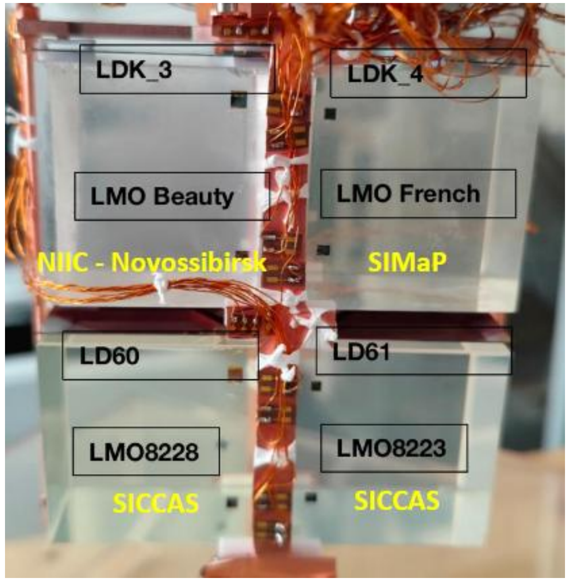
What's new?

- Light detectors with NTL amplification
- Changes to the LD holding system to mitigate the noise

Status of crystal procurement

Because of the war against Ukraine the procurement of enriched crystals from Russia is impossible

Possible **alternative suppliers**:

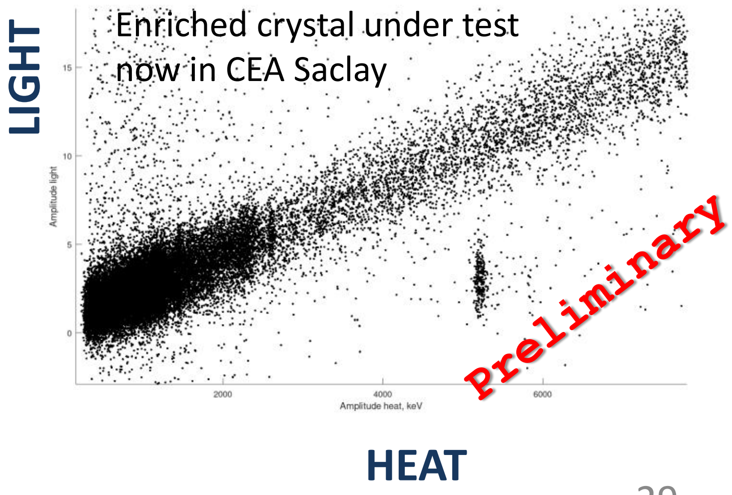


Baseline candidate: SICCAS (Shanghai, China)

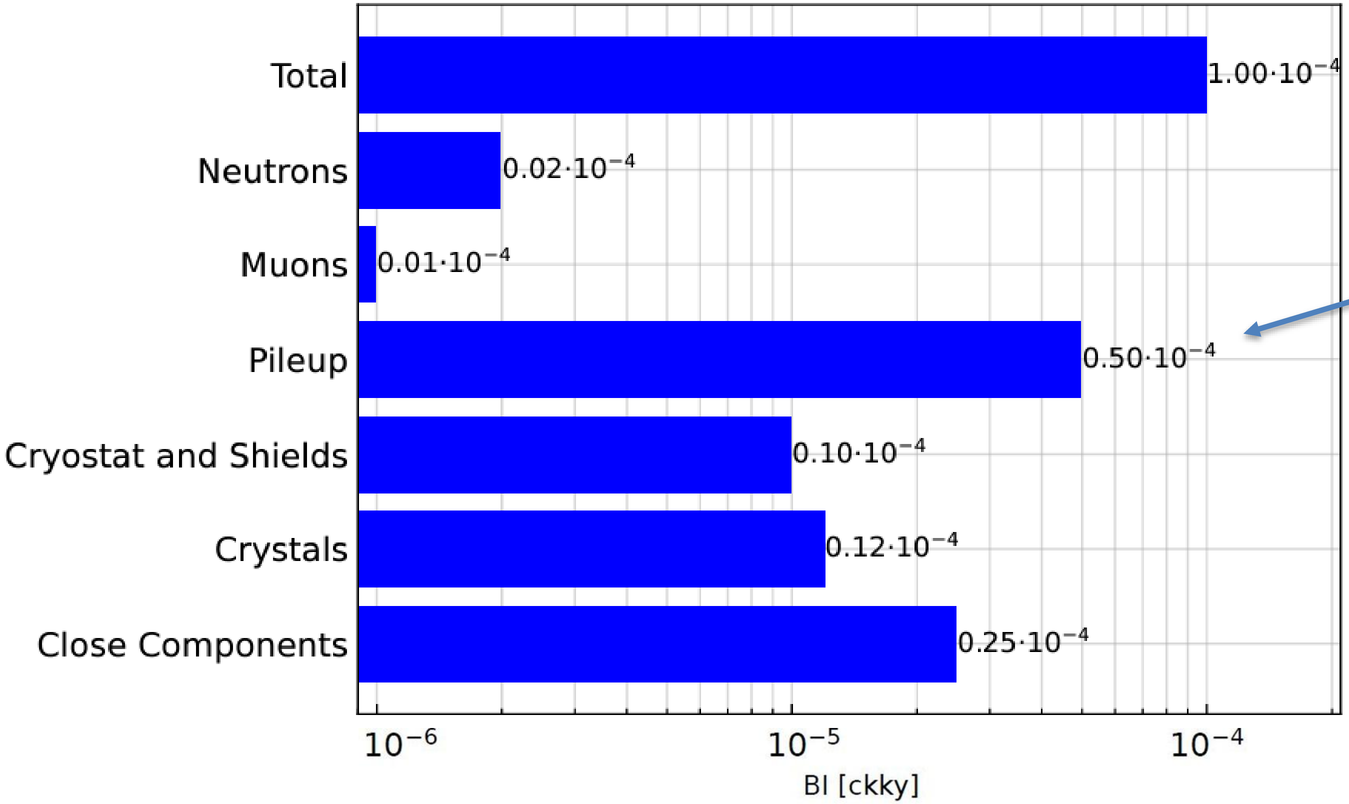
- Already produced 988 TeO_2 crystals for CUORE
- It is ready to produce 1596 $Li_2^{100}MoO_4$ crystals with 95 % enrichment
- The first sample of isotope, measured by ICP-MS at LNGS, fully matches radiopurity requirements
- Pre-production is ongoing:
  - set of several natural crystals and four enriched crystals were successfully tested ir cryogenic facility in LNGS, in Orsay (IJCLab) and Saclay (CEA/IRFU)

Investigating opportunities for production in France:

- We received a first natural Li_2MoO_4 crystal from Matias Velázquez (Univ. Grenob Alpes, CNRS, Grenoble INP, SIMaP, France) and performed the first tests in Orsay cryogenic facility – it will measured underground in the CROSS demonstrator
- The first Li_2MoO_4 crystals from Luxium Solutions were grown and were successfully tested



CUPID background budget

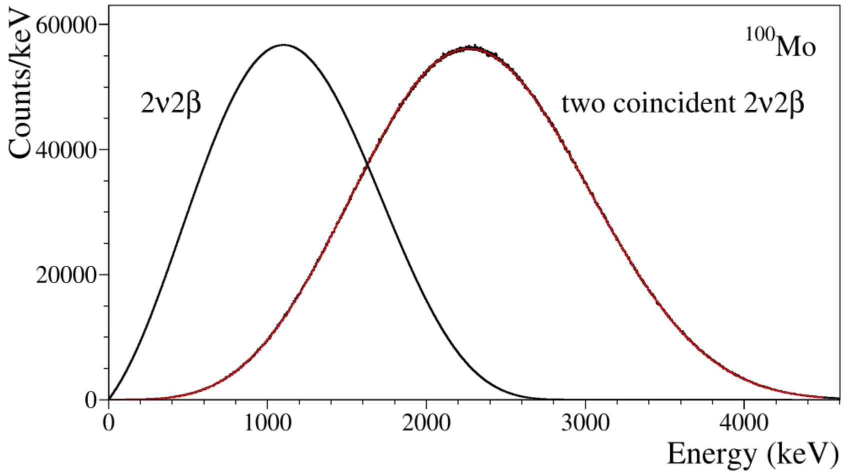


Two orders of magnitude better than in CUORE

CUPID background goal:

BI = 10^{-4} counts/keV/kg/year (ckky)

Dominant contributions: **pile-up events** (random coincidences of ordinary $2\nu\beta\beta$ events)



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

Phys. Rev. D 110 (2024) 052003

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

Conservative projections based on current available data: BI = 1.1 x 10^{-4} ckky

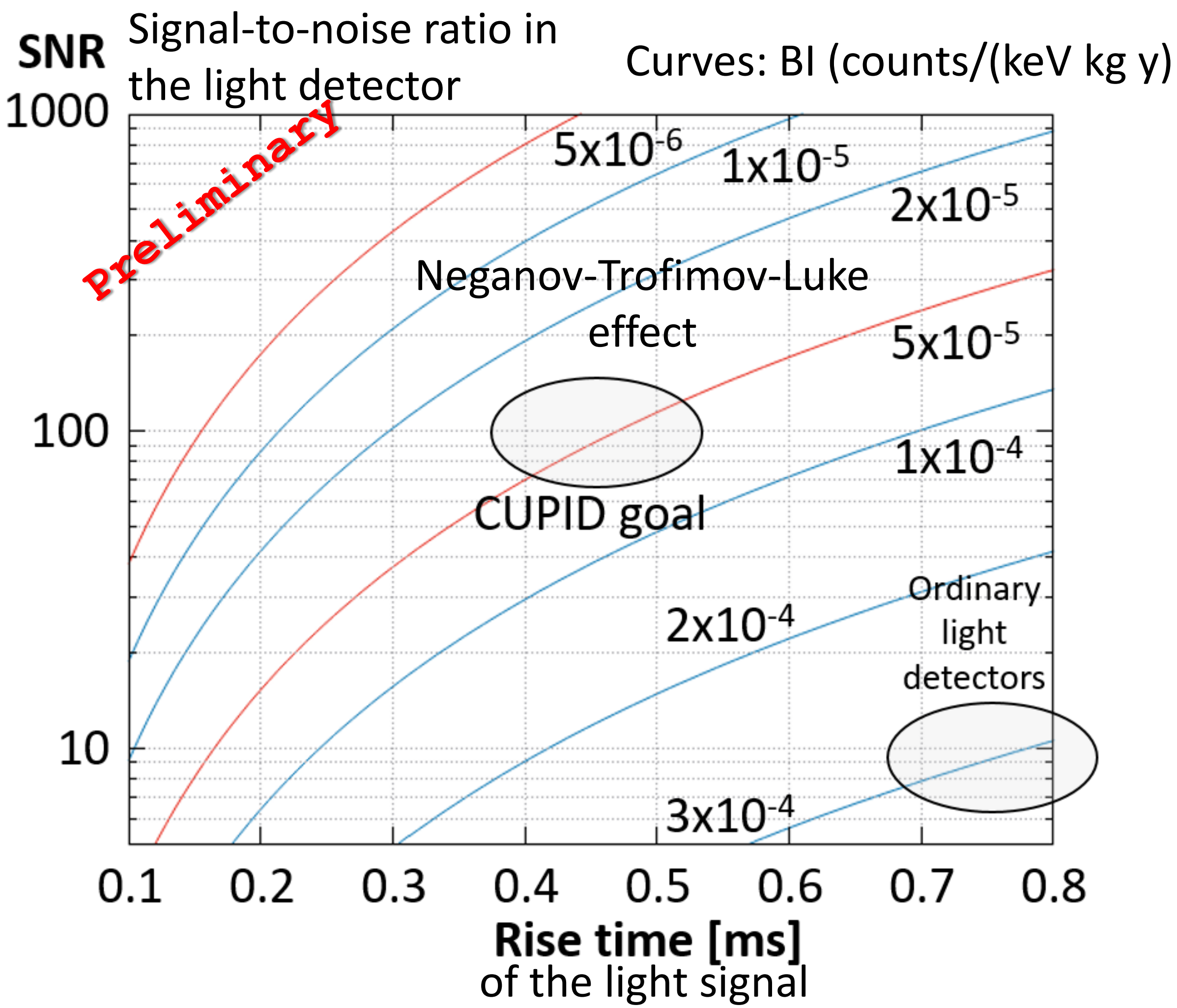
Fastest $2\nu2\beta$ decay: $T_{1/2} \sim 7.1 \times 10^{18}$ y

Slow response of bolometric signals

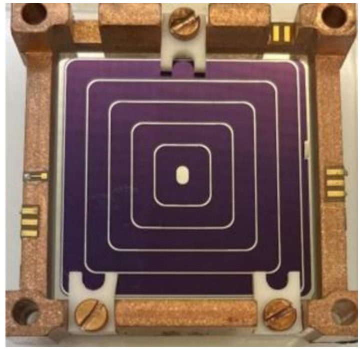
- ~ 3 mBq in each crystal
- ~ 10 ms ← Heat channel
- ~ 0.5 - 1 ms ← Light channel

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)**



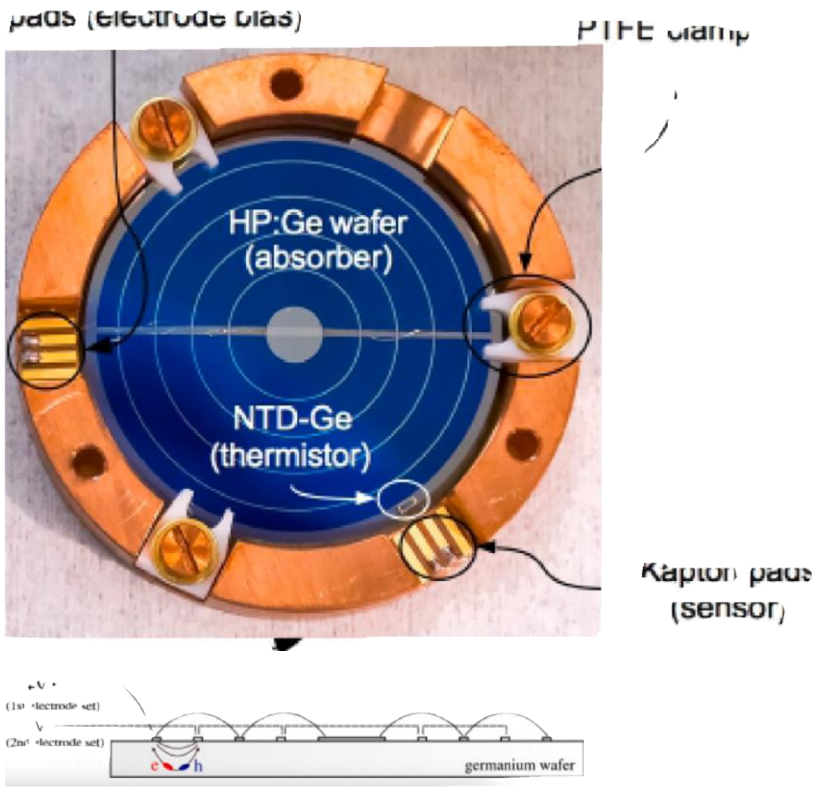
- Establish an **electric field** in the light detector wafer via a set of Al electrodes
- Electron-hole pairs created by light absorption drift in the field and produce **additional heat**
- An **amplification of the thermal signal** by a factor 10-20 is technically possible
- **SNR is increased by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

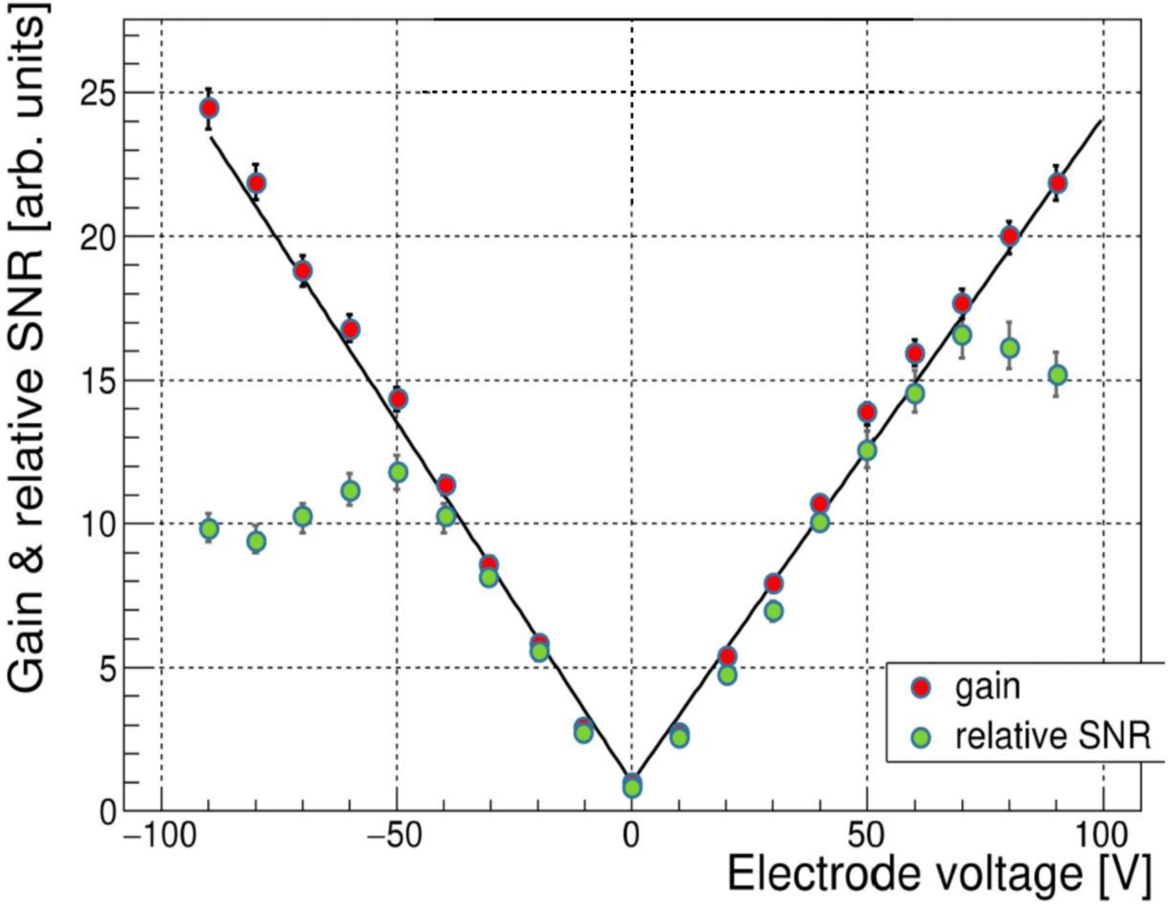


Neganov-Trofimov-Luke light detectors

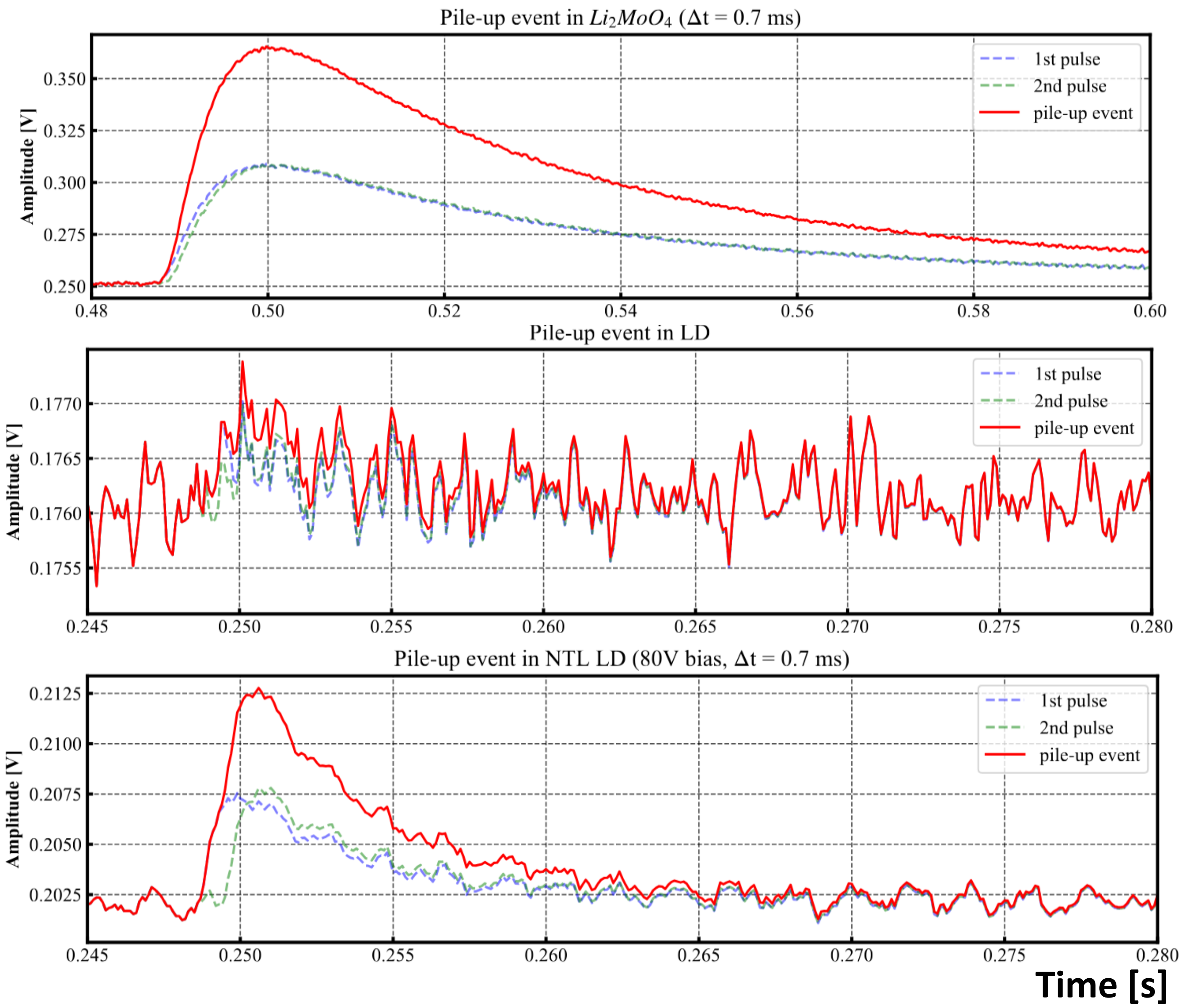
NIMA 940, 320 (2019)

$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$





How NTL helps rejection of pile-up



Pile-up event as seen by the **heat channel**
Summed amplitude → 0ν2β 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

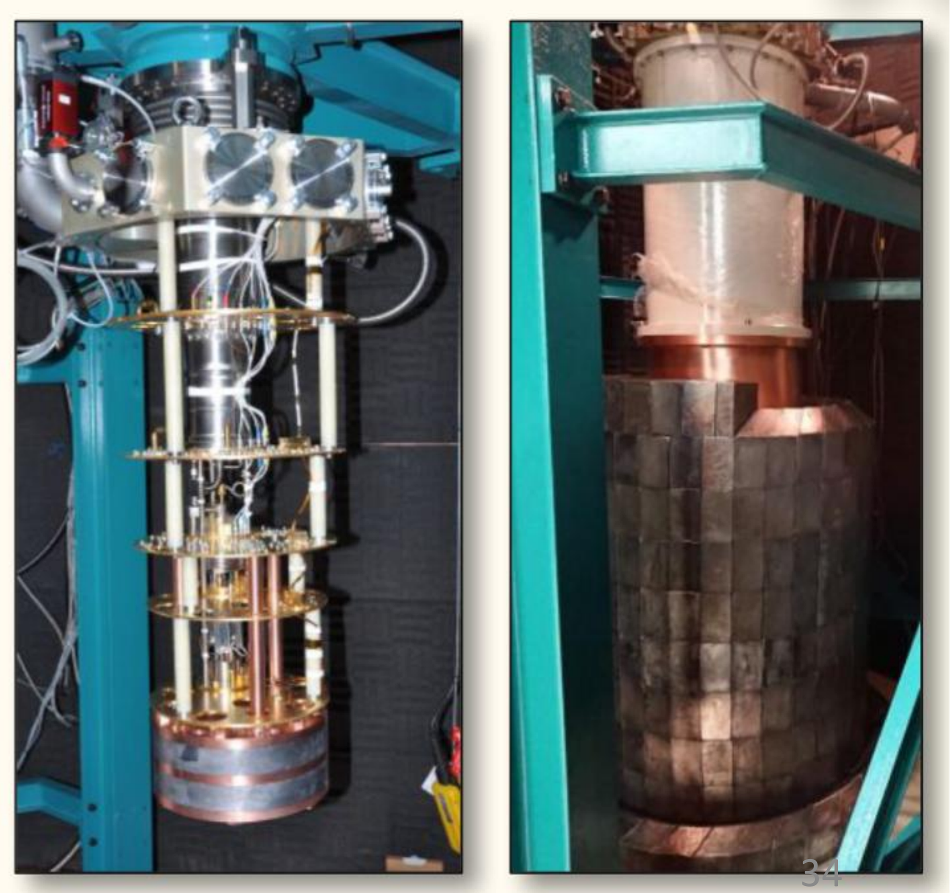
Same event seen by the **light channel**
Neganov-Trofimov-Luke effect with ΔV=80 V
Pulse shape discrimination is possible

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

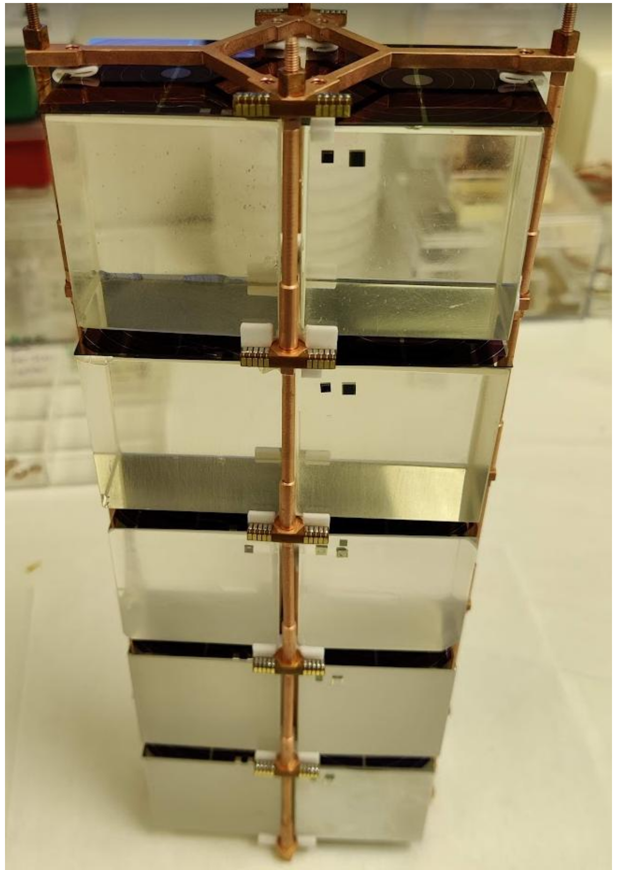
New technologies:

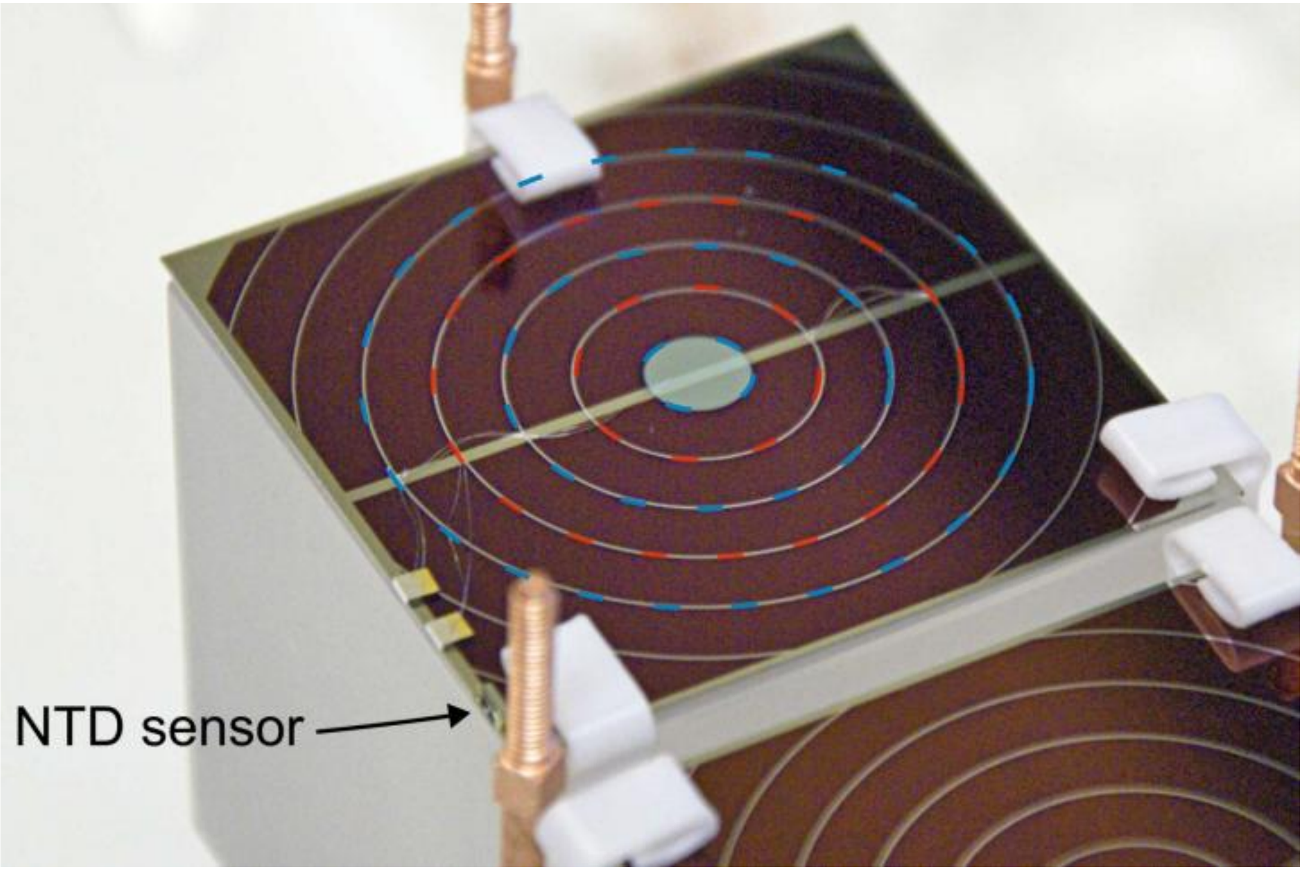
- **Surface film coating** of crystals to discriminate between bulk and α/β surface events
- **Neganov-Trofimov-Luke (NTL) Light Detectors** development and optimization

CROSS project: NTL light detectors

- Crucial test in Canfranc showed that **the CUPID pile-up background goal is achievable thanks to NTL**
- Tower of 10 crystals and 10 NTL light detectors operated in the Canfranc CROSS facility

arXiv:2507.15732



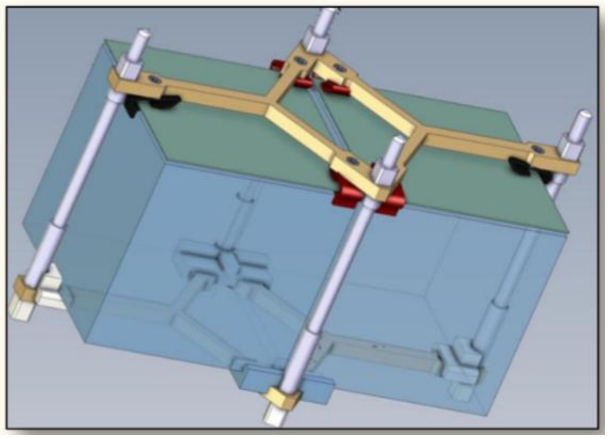


CROSS demonstrator: structure

3 towers with 7 floors each

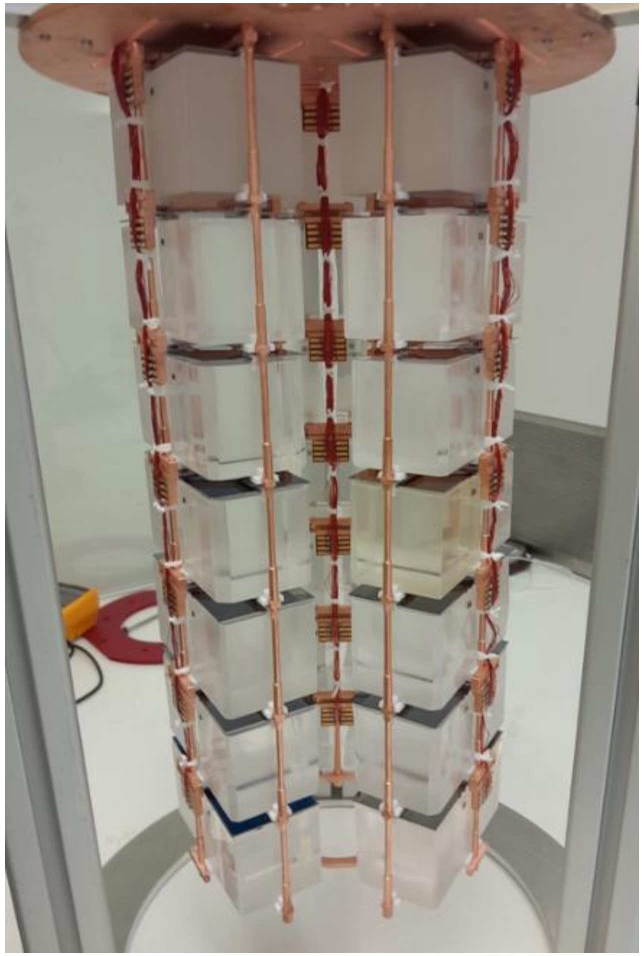
Test of different light detectors in each tower:

- 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 $^{130}TeO_2$

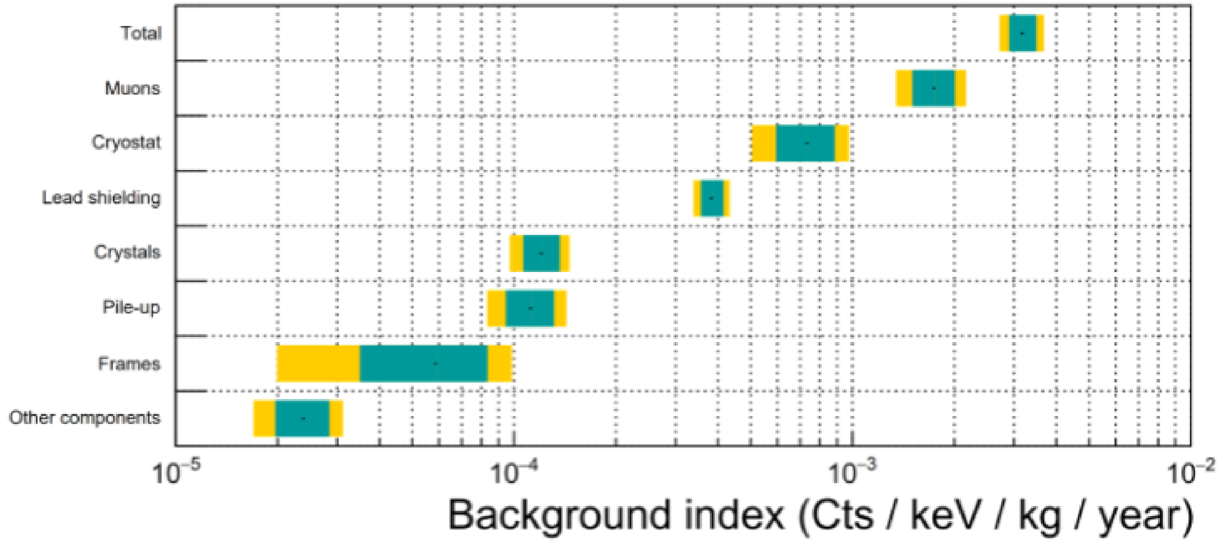
- **Total mass of ^{100}Mo: 4.7 kg**
- **Total mass of ^{130}Te: 2.6 kg**

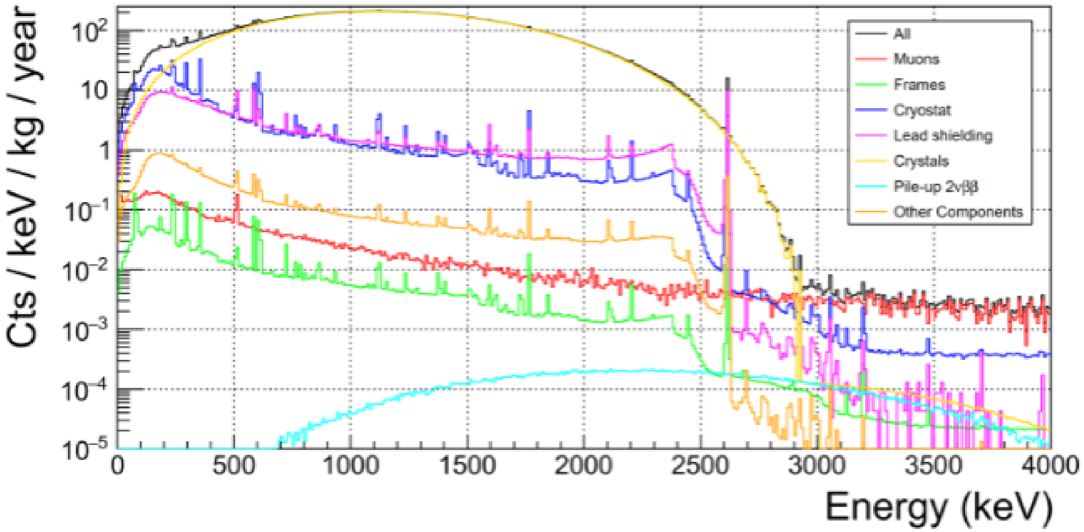
Detectors now installed in the Canfranc underground laboratory

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

CROSS demonstrator: sensitivity

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





Assuming 2 years live time of the experiment CROSS experiment will be able to set a limit at 90% confidence level on the $^{100}\mathrm{Mo}\ 0\nu\beta\beta$:

$$\mathbf{T_{1/2}^{0\nu\beta\beta} > 9.36 \cdot 10^{24} yr}, \text{ corresponding to } \mathbf{m_{\beta\beta} < (126 - 213)\ meV}$$

Current limits on $^{100}\mathrm{Mo}\ 0\nu\beta\beta$:

- CUPID-Mo: half-life $\mathbf{T_{1/2}^{0\nu} > 1.8 \cdot 10^{24}\ yr}$
- AMORE-I: half-life $\mathbf{T_{1/2}^{0\nu} > 2.9 \cdot 10^{24}\ yr}$

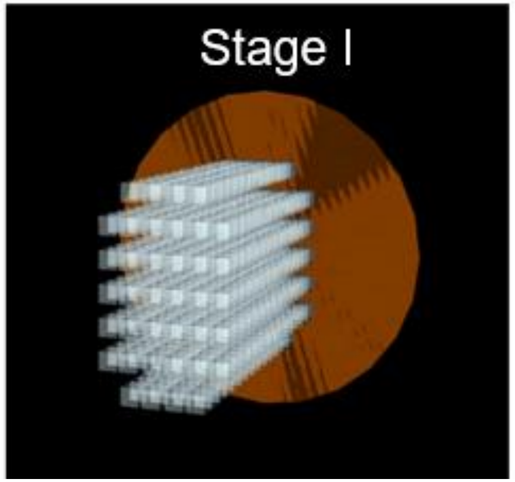
In both cases, sensitivities higher than the current best world limit on $^{100}\mathrm{Mo}\ 0\nu2\beta$

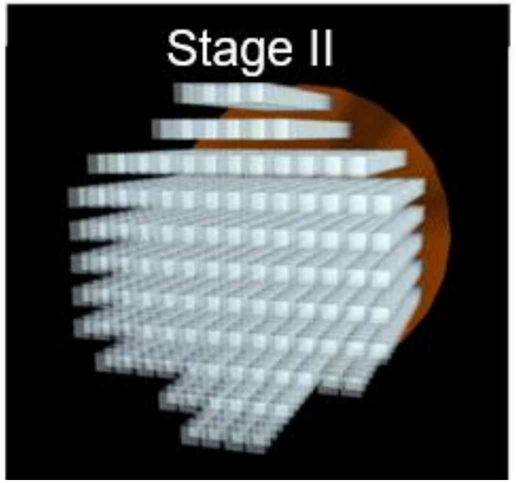
Coming back to CUPID: staged development

In 2024, the collaboration decided to move to a **staged deployment** for CUPID implementation

Parallelized approach for the construction and commissioning of the experiment:

- **stage I = first ⅓ crystals**
- **stage II = remaining ⅔ crystals**





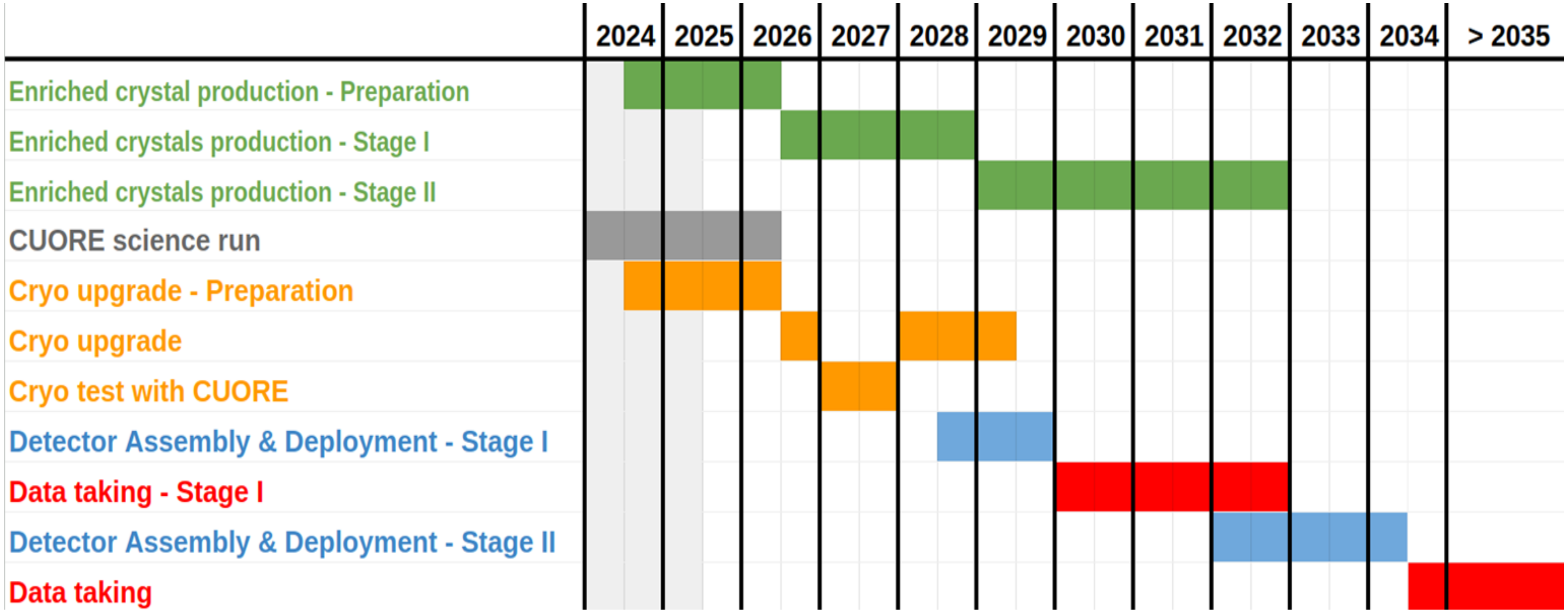
Advantages

- **early data taking (2030)** while the remaining crystals are produced
- helps retain critical detector expertise during CUORE →CUPID transition
- further room for optimization, improvement and risk mitigation strategy

Detector configuration in the cryostat

CUPID timeline

- **construction already started**
- ready for **enriched crystal production** by the beginning of 2026
- **staged deployment** to enable first science data by 2030



CUPID sensitivity

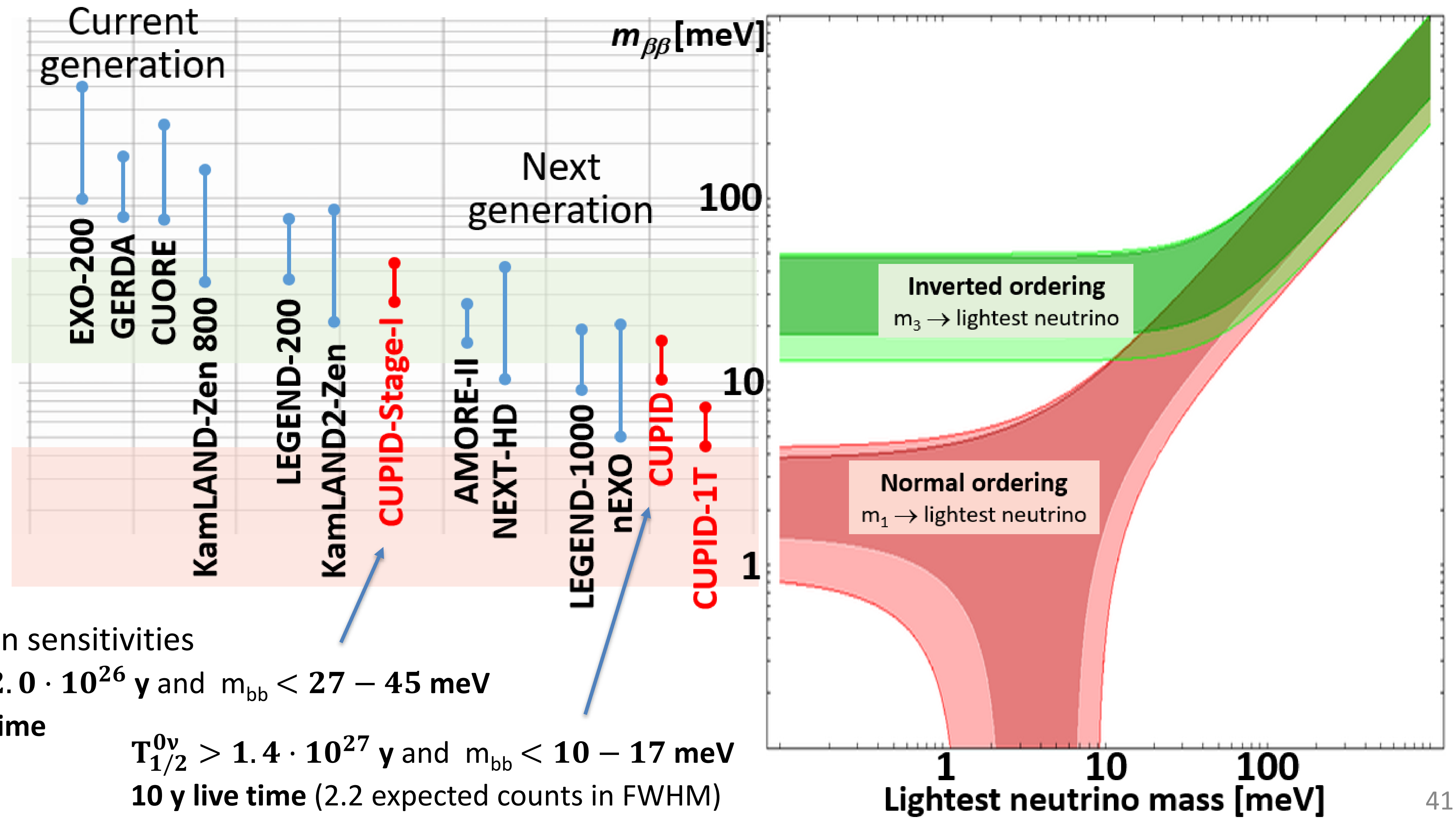
- **Exclusion sensitivity 90% C.I.** (10 yrs livetime - 240 kg ^{100}Mo + 5 keV FWHM)
  $T^{0\nu}_{1/2}$ > 1.4 x 10^{27} yr **$m_{\beta\beta}$ < (10-17) meV**

- **3 σ - discovery sensitivity**
  $T^{0\nu}_{1/2}$ > 1 x 10^{27} yr **$m_{\beta\beta}$ < (12-21) 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



Exclusion sensitivities

$\mathbf{T^{0\nu}_{1/2} > 2.0 \cdot 10^{26}}$ **y** and $m_{bb} < \mathbf{27 - 45}$ **meV**

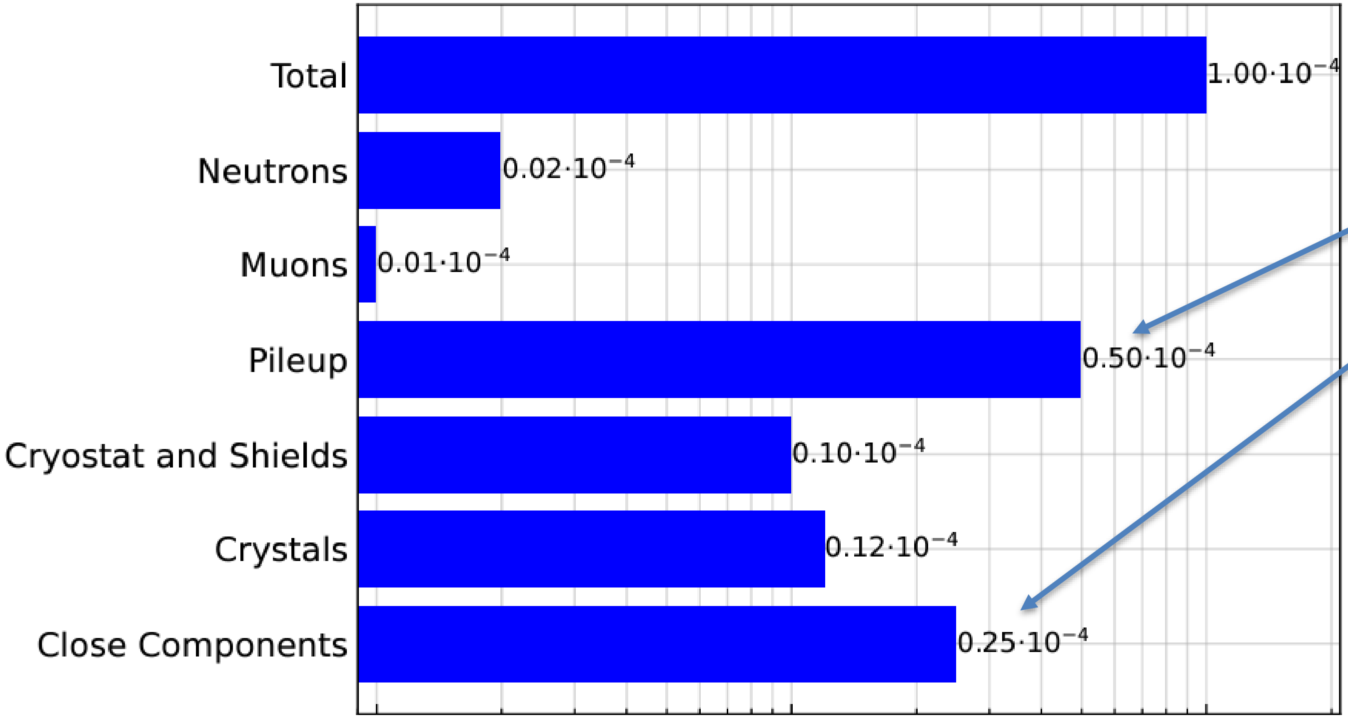
3 y live time

$\mathbf{T^{0\nu}_{1/2} > 1.4 \cdot 10^{27}}$ **y** and $m_{bb} < \mathbf{10 - 17}$ **meV**

10 y live time (2.2 expected counts in FWHM)

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 = 10^{-5} c/(keV kg y)** → **(1/10)x CUPID** (0.89 count/10y expected in FWHM)



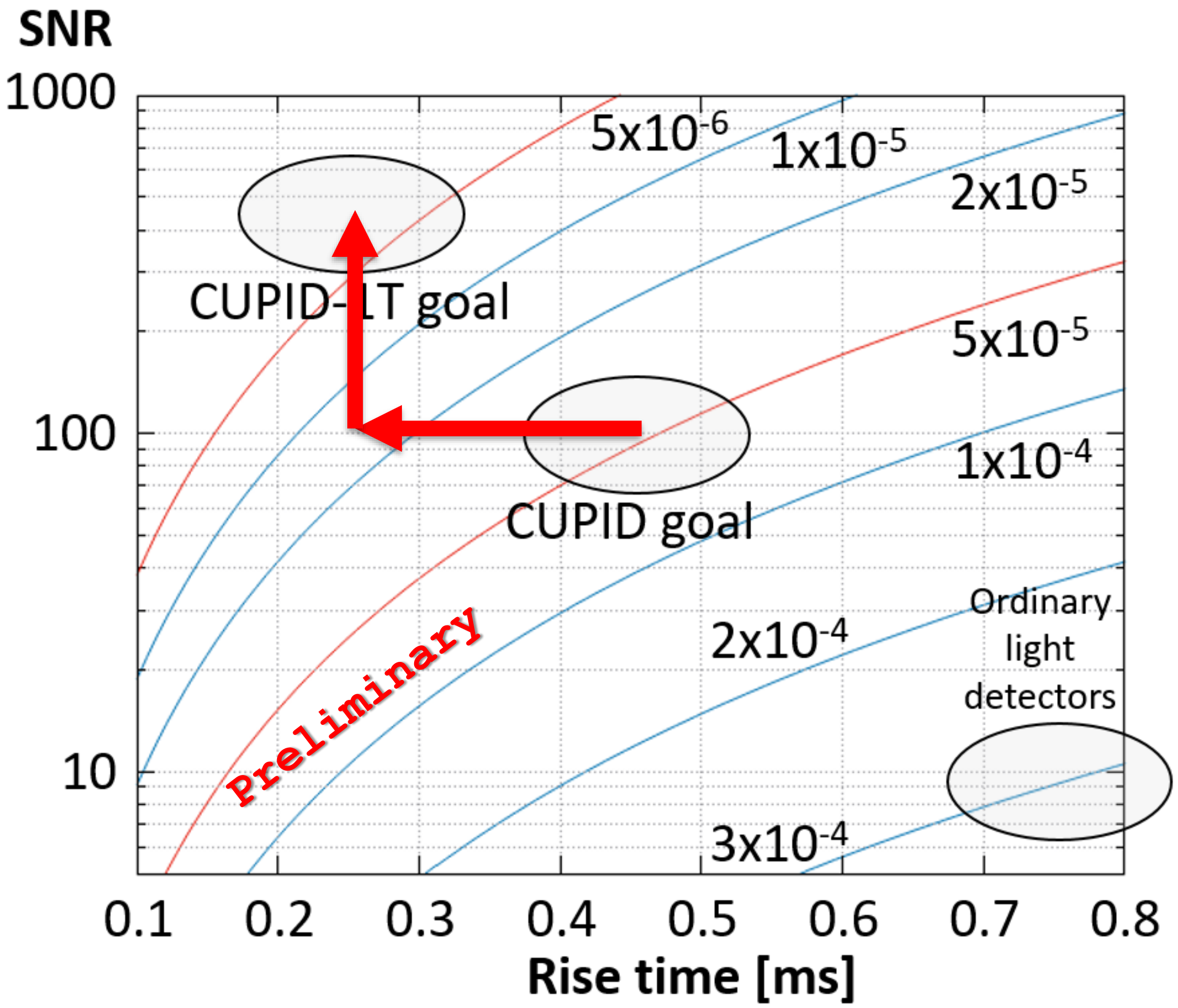
These two components must be reduced by one order of magnitude

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

Close components: β surface radioactivity:
- Successful implementation of CROSS surface sensitivity
- New approach: BINGO assembly technique

Is CUPID-1T feasible?

- **Pile-up**



Light detector performance

With respect to CUPID

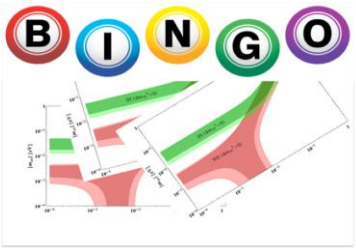
- Increase SNR x5
- Reduce Rise-time x2

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



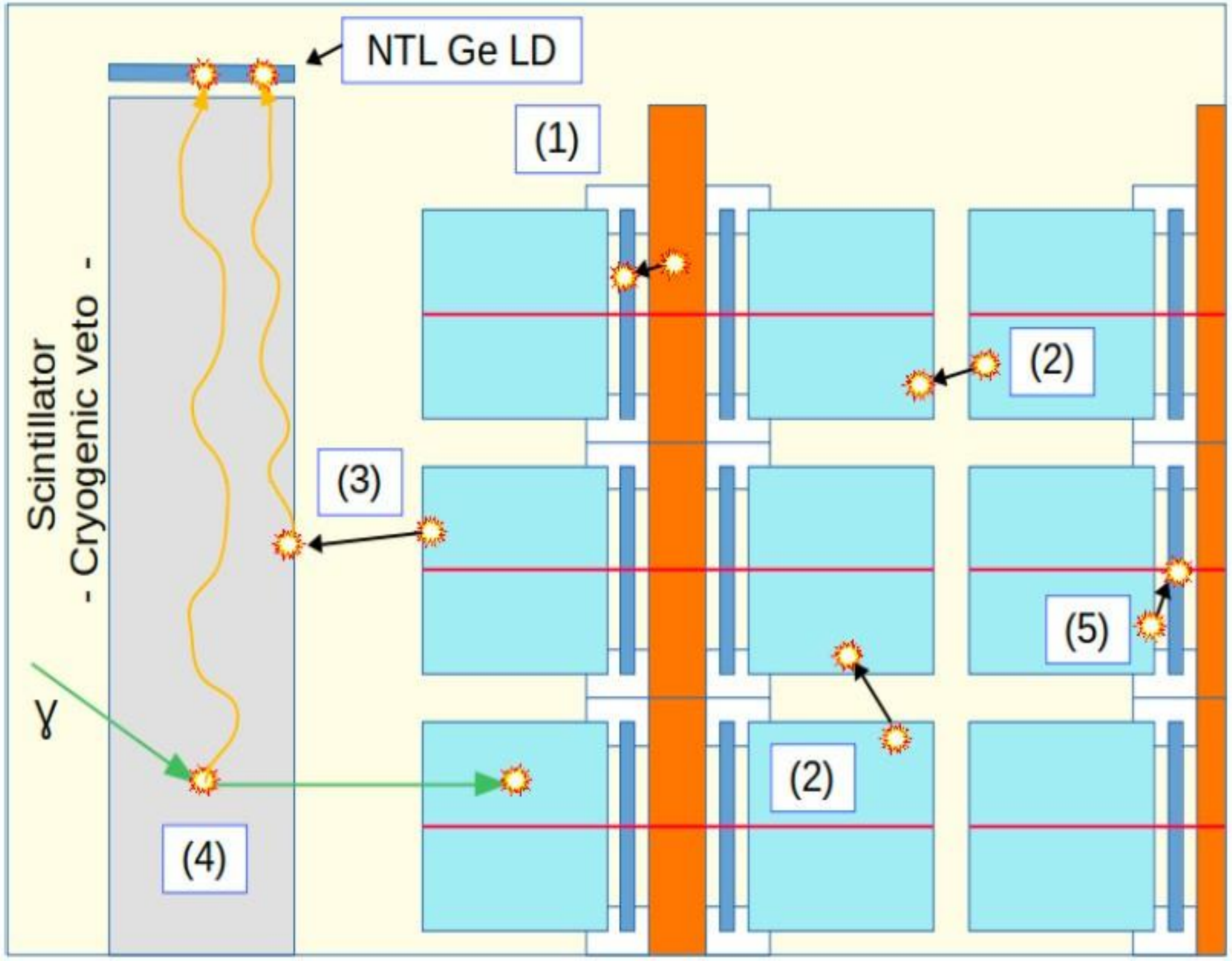
Bolometric search for $0\nu2\beta$ decay in ^{130}Te and ^{100}Mo

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

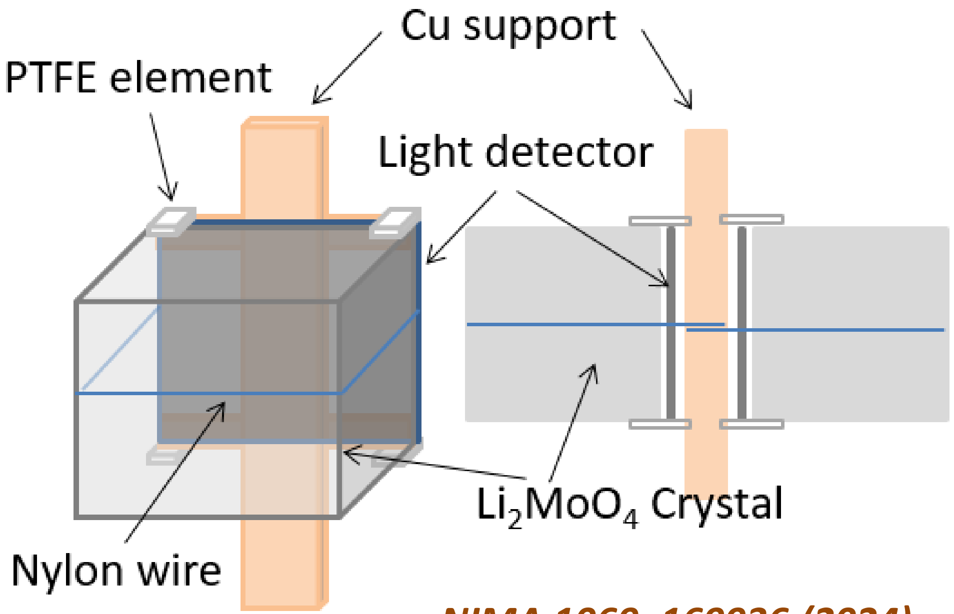
(2) Active cryogenic veto:
Suppression of background from high energy γ's surrounding detectors volume by a scintillator (BGO) operating at the base temperature

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

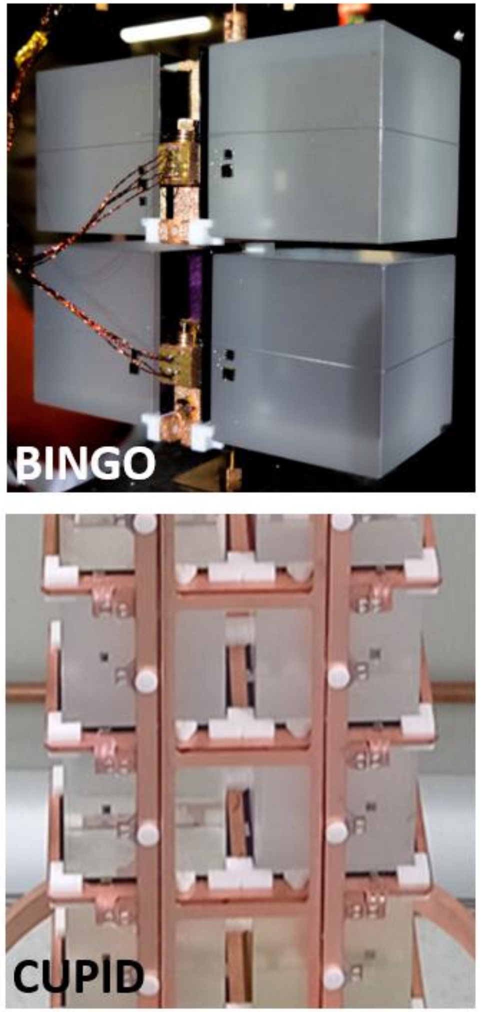


Surface background and BINGO

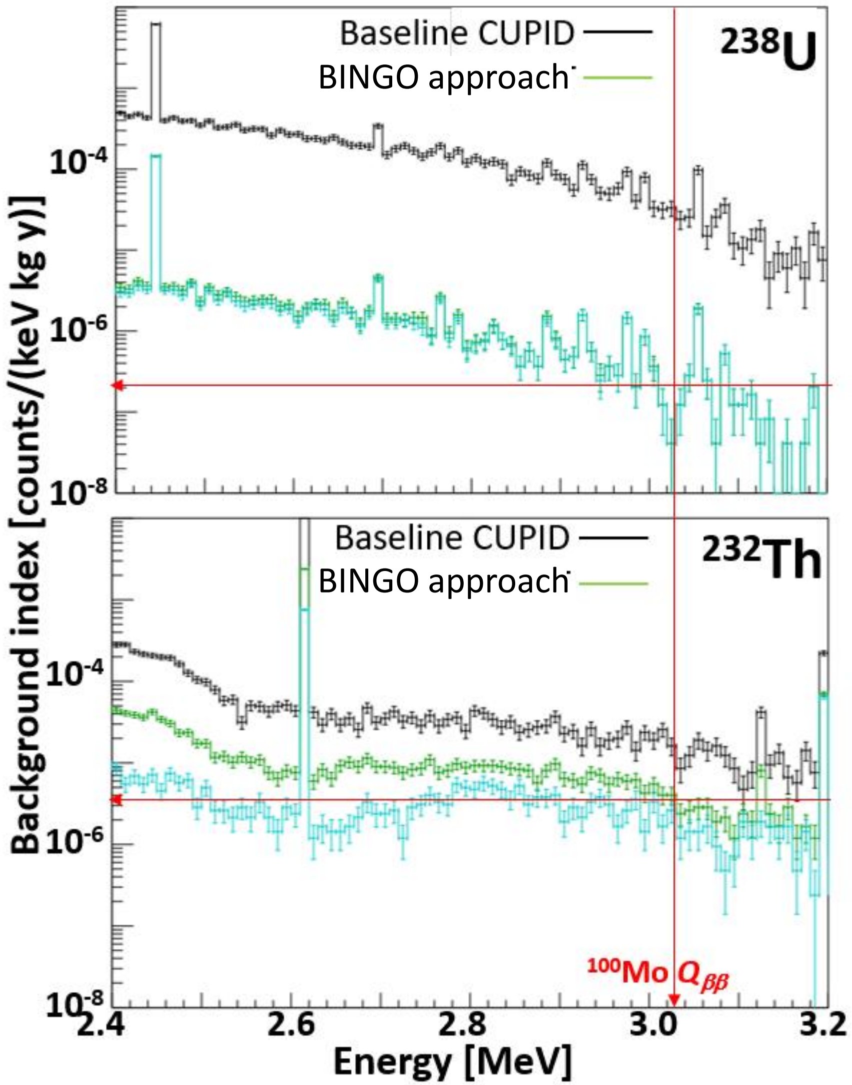
Mitigate background from Close components in CUPID



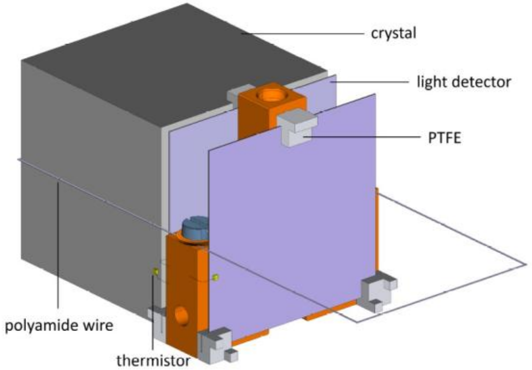
NIMA 1069, 169936 (2024)

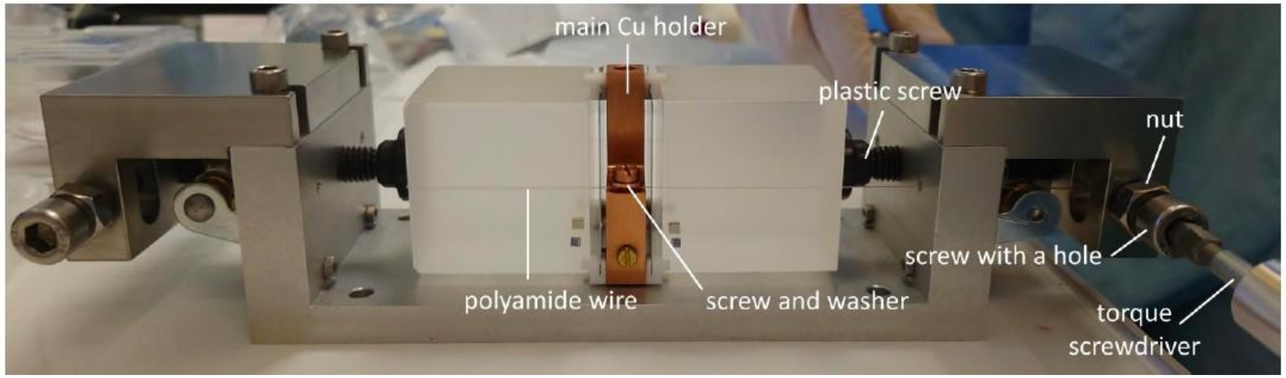


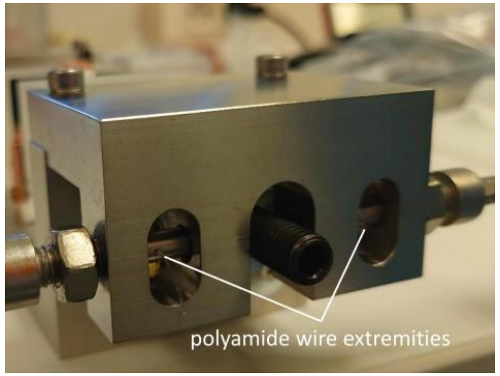
Simulation CUPID vs. BINGO



A revolutionary detector assembly

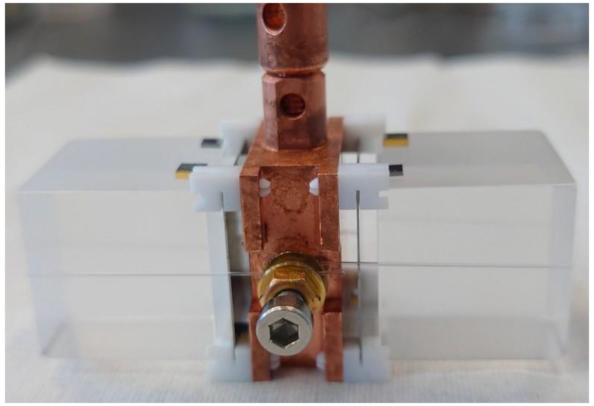




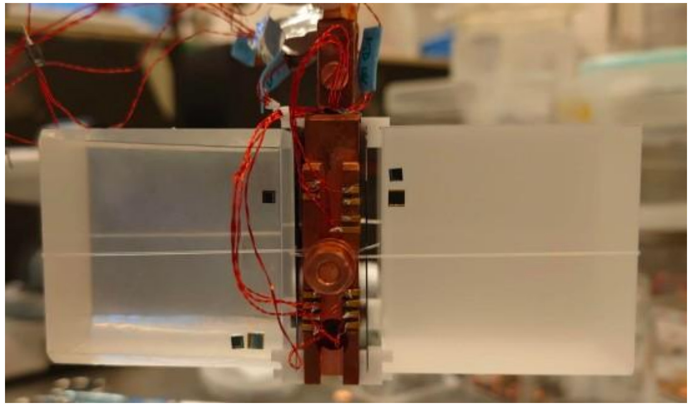


Polyamide wires are tensioned like violin strings at 4 + 4 kg

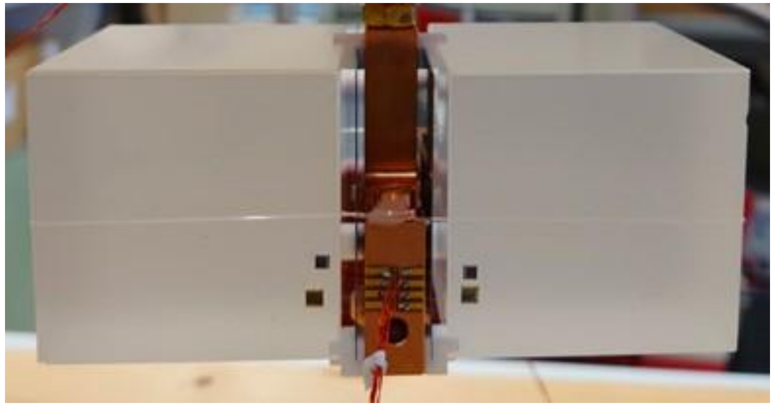
First prototype with small LMO crystals



Full-size LMO crystals

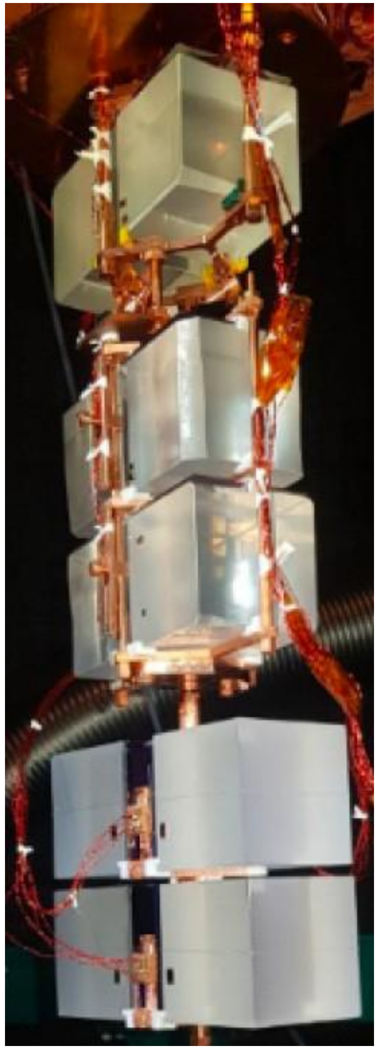


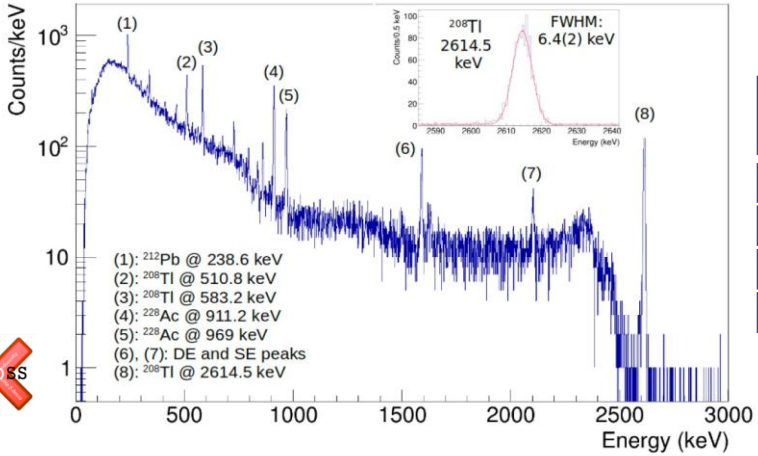
Full-size TeO_2 crystals

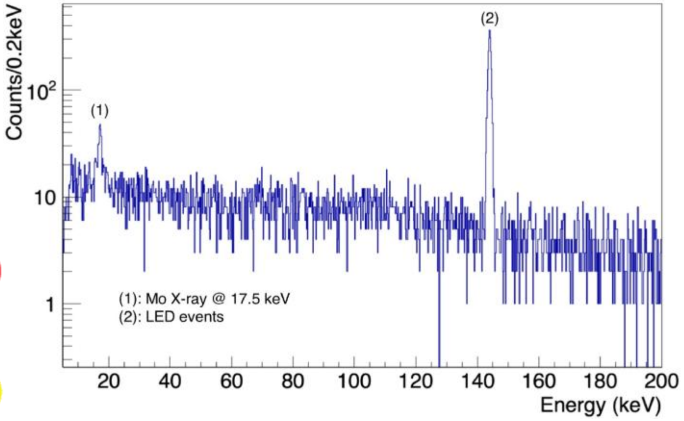


All the assembly prototypes were tested at the base temperature 15-20 mK above ground @IJCLab

BINGO detectors work!







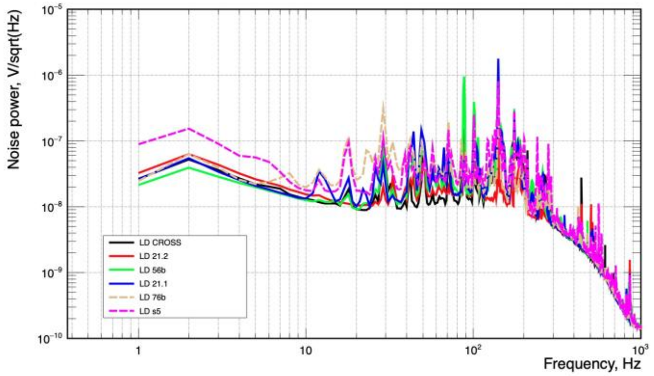
LMO crystals performance

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

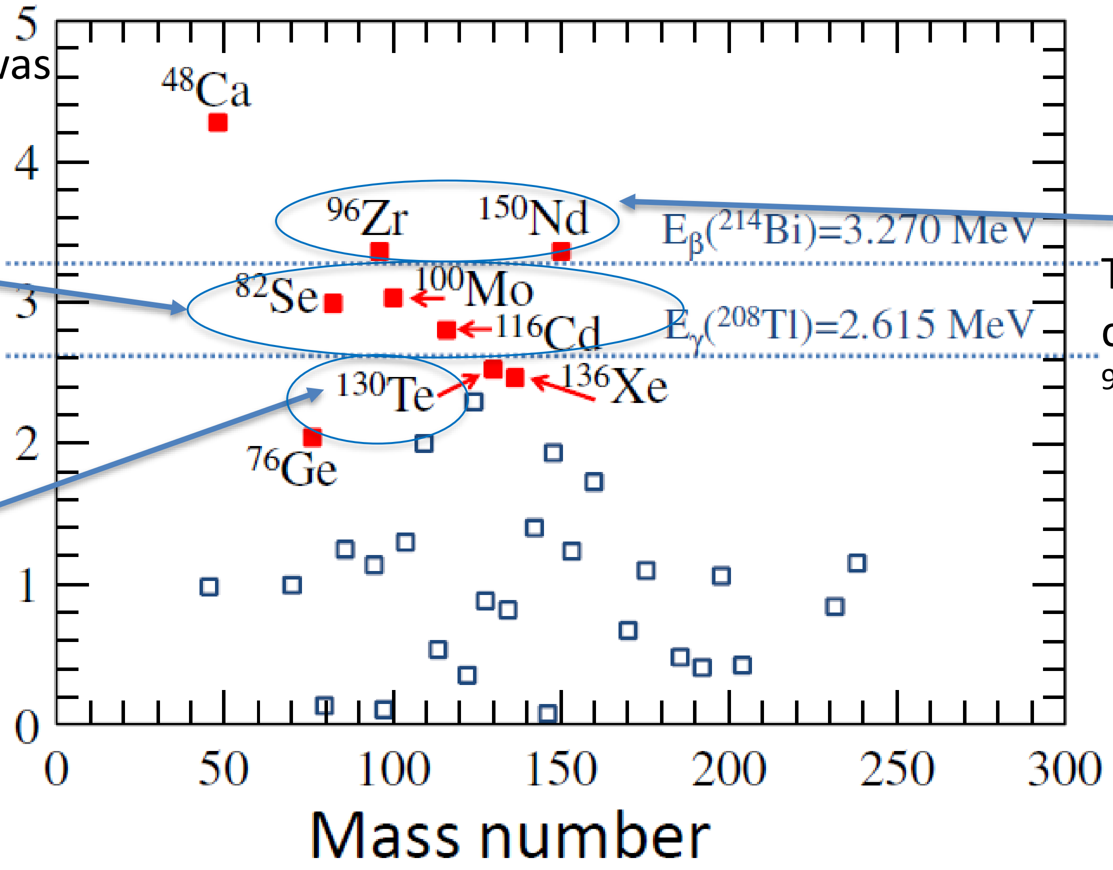
Scintillating bolometer technology was successfully applied to
^{82}Se (ZnSe – **CUPID-0** experiment)
^{116}Cd ($CdWO_4$)

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

Summary and final considerations

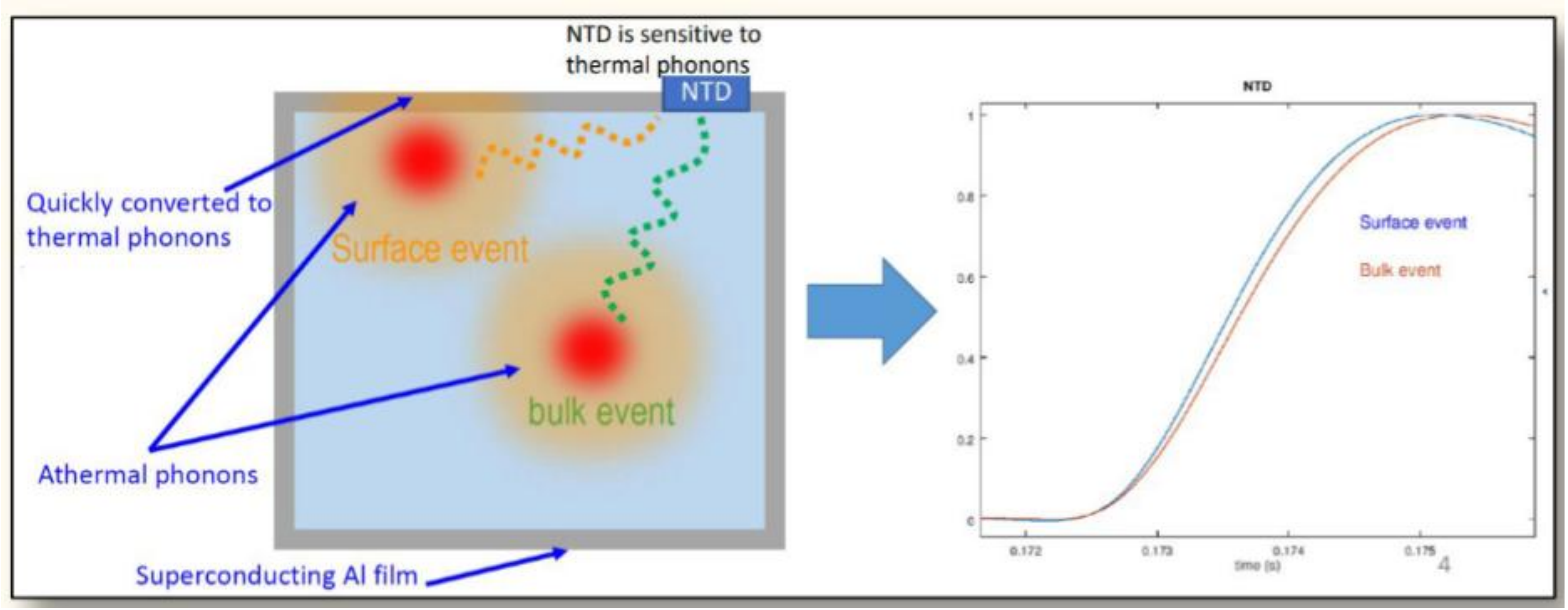
- The **infrastructure for CUPID** already **exists** (**CUORE** cryostat, **LNGS**, Italy)
- **Basic technology** demonstrated in **CUPID-Mo** (EDELWEISS cryostat, **Modane**, France)
- The **performance** of the single module and of the basic tower are promising
- **Crystallization** and **enrichement** at large scale are **possible** (Chinese production line)
- **Data-driven background model** indicates **b$\sim$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: BINGO technologies** can reduce the Close components background
- Potential **multi-isotope approach**

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

- 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** → $T_C \sim 0.7$ K (proximity effect)

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

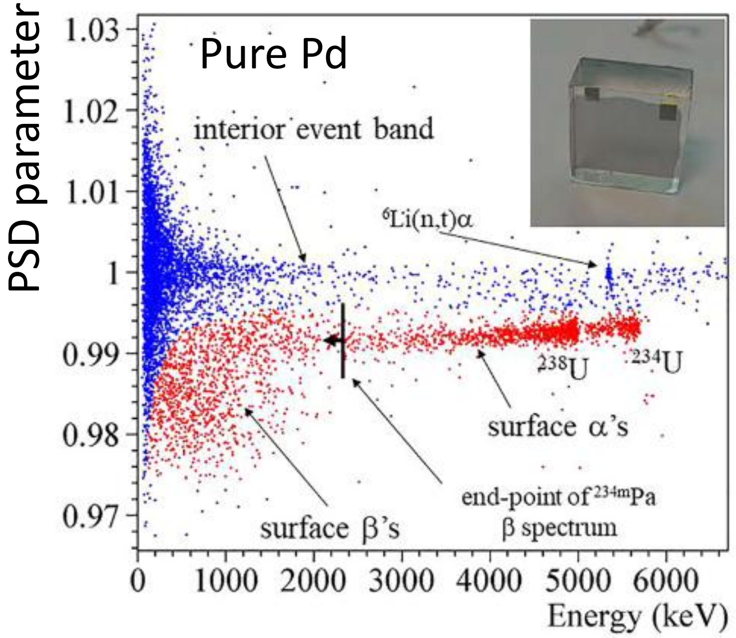
Best compromise between

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

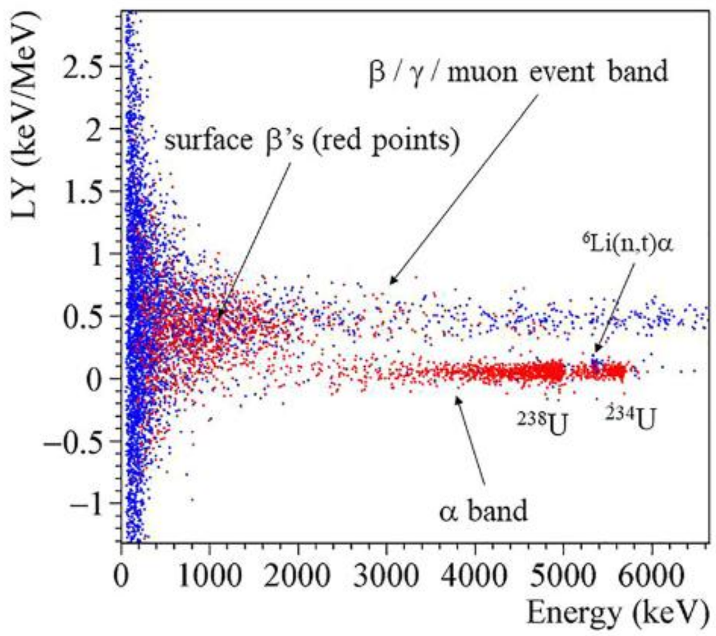
Sample are irradiated with an U source providing both α (4.2 and 4.7 MeV) and β (end-point at 2.2 MeV)

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