IDPASC

15-25 July 2025

The International Doctorate Network in Particle Physics, Astrophysics and Cosmology

July 23rd , 2025

Neutrinoless double beta decay: The most sensitive probe of neutrino nature

Andrea Giuliani

IJCLab, Orsay, France

Outline

1. Double beta decay and physics beyond the Standard Model

2. Experimental challenge and state-of-the-art

3. The bolometric technique: principle and experiments

Outline

1. **Double beta decay and physics beyond the Standard Model**

2. Experimental challenge and state-of-the-art

3. The bolometric technique: principle and experiments

Beta decays and new physics

Single β decay

Wolfgang Pauli,
"Letter to the radioactive ladies and gentlemen",
(1930)

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen

Enrico Fermi,
"Attempt at a beta-ray emission theory",
(1933)

· VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

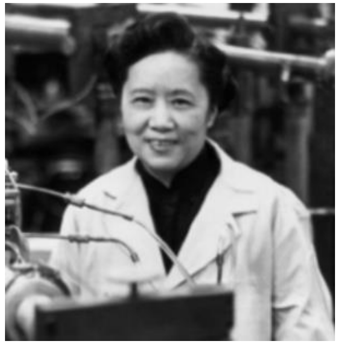
Nota del prof. ENRICO FERMI

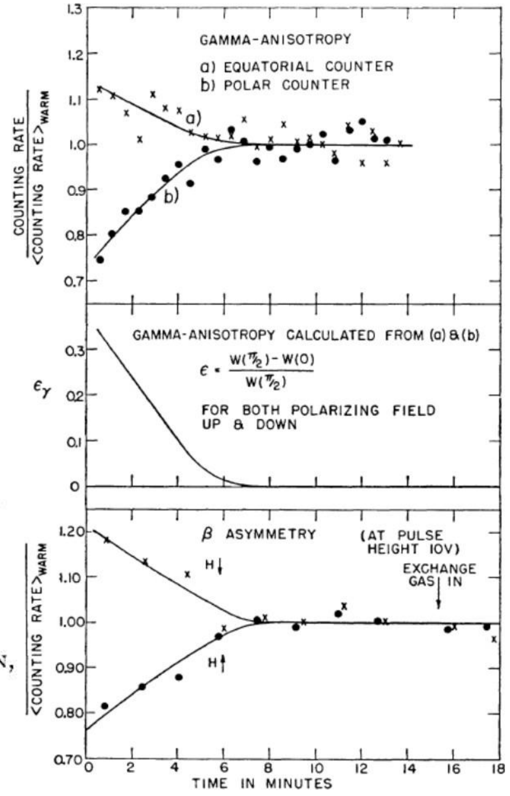
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Beta decays and new physics

$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$

Chieng-Shiung Wu,
Parity Violation
(1956)





Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

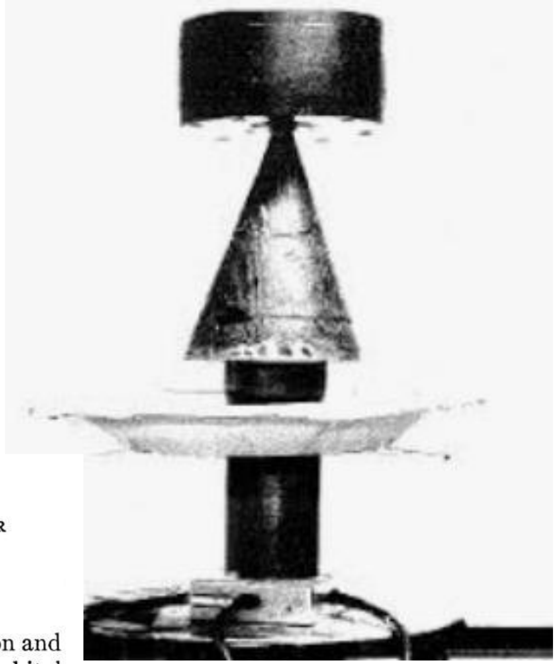
AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*
(Received January 15, 1957)

At millikelvin temperatures!

$Eu + e^- \rightarrow Sm^* + \nu_e \rightarrow Sm + \gamma + \nu_e$

Maurice Goldhaber,
Helicity of neutrinos
(1957)



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Double beta decay

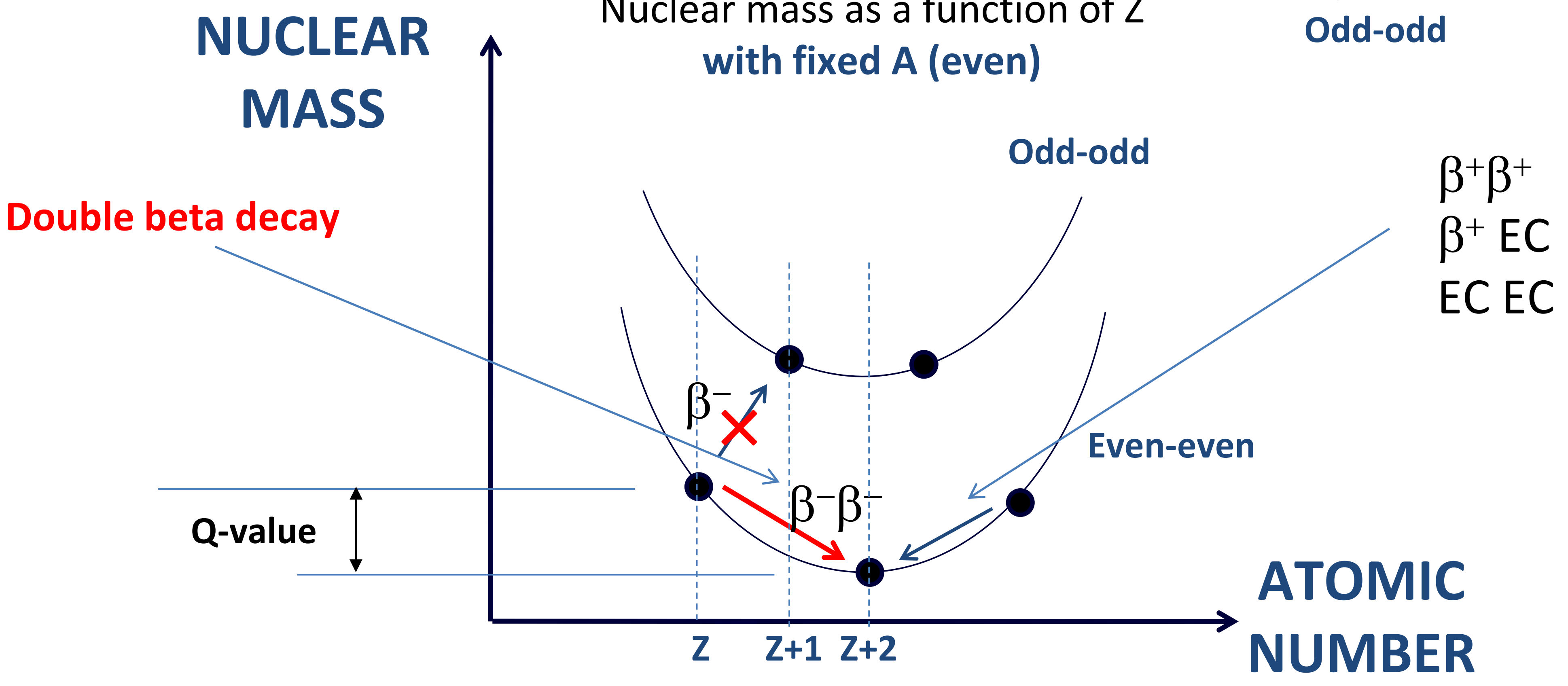
Weiszaecker's formula for the binding energy of a nucleus

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

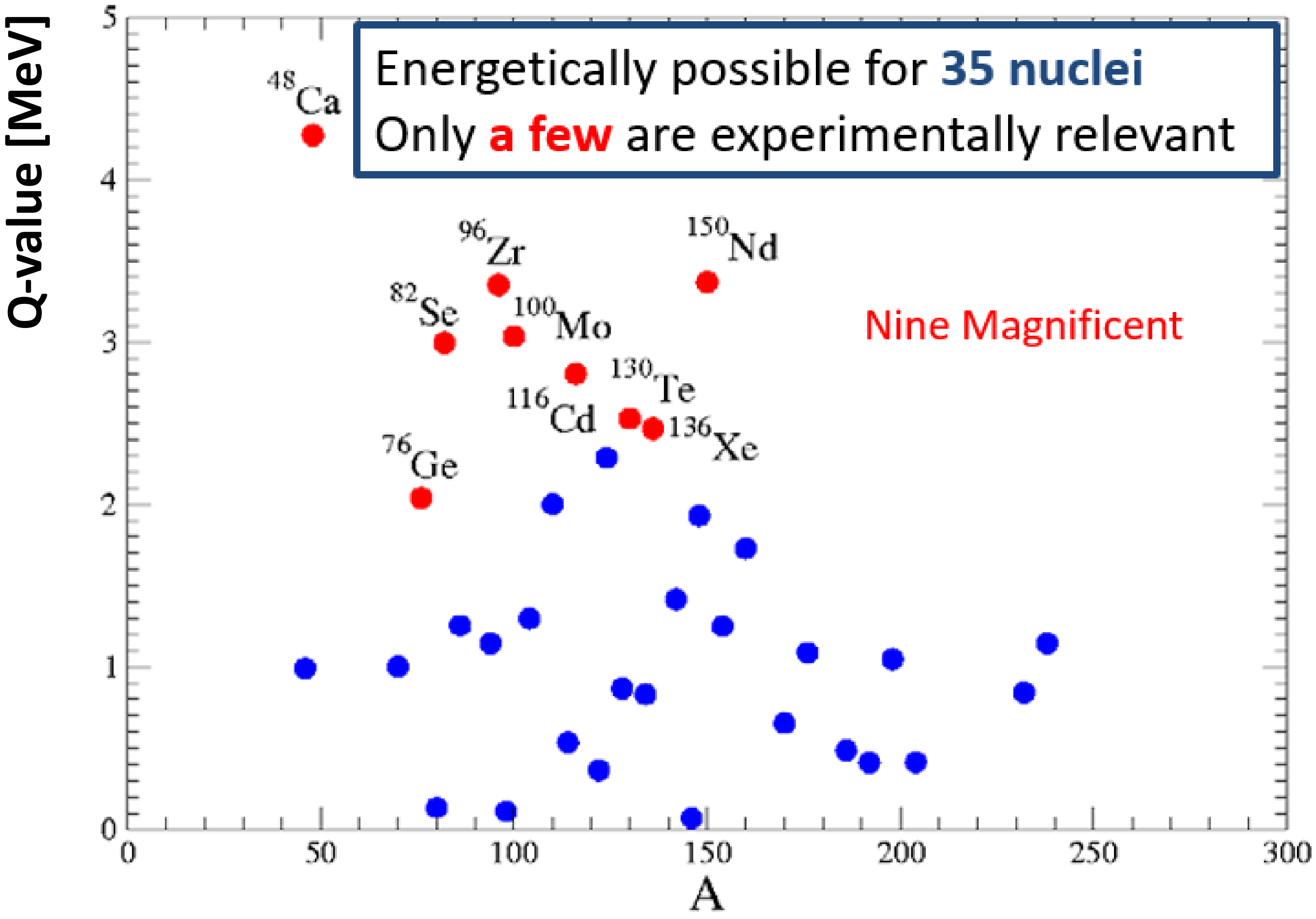
Even-even

Odd-odd

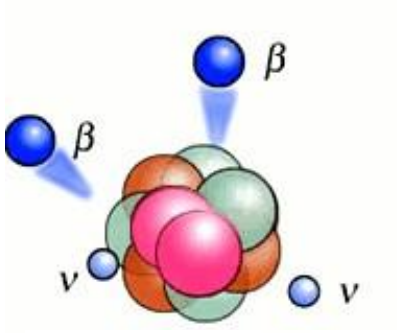
Nuclear mass as a function of Z
with fixed A (even)



Double beta decay



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)

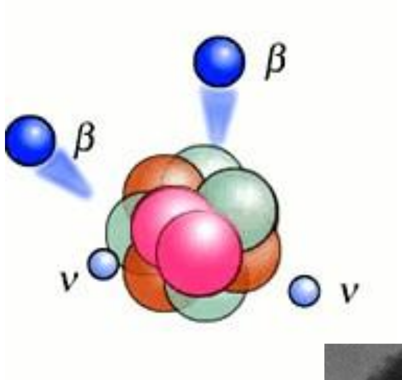
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

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



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

In the Dirac-Fermi theory of beta decay, neutrinos and antineutrinos are different particles

DIRAC or **MAJORANA**

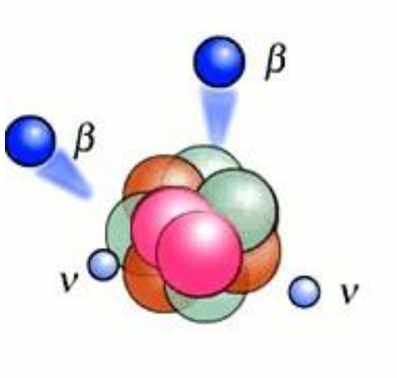
$$\nu \neq \bar{\nu} \qquad \nu \equiv \bar{\nu}$$

As electrons and positrons, neutrinos and antineutrinos have different lepton numbers
$L(\nu_e, e^-) = +1; L(\bar{\nu}_e, e^+) = -1$

Lepton number is not a good quantum number

The quest for the nature of neutrino

Double beta decay



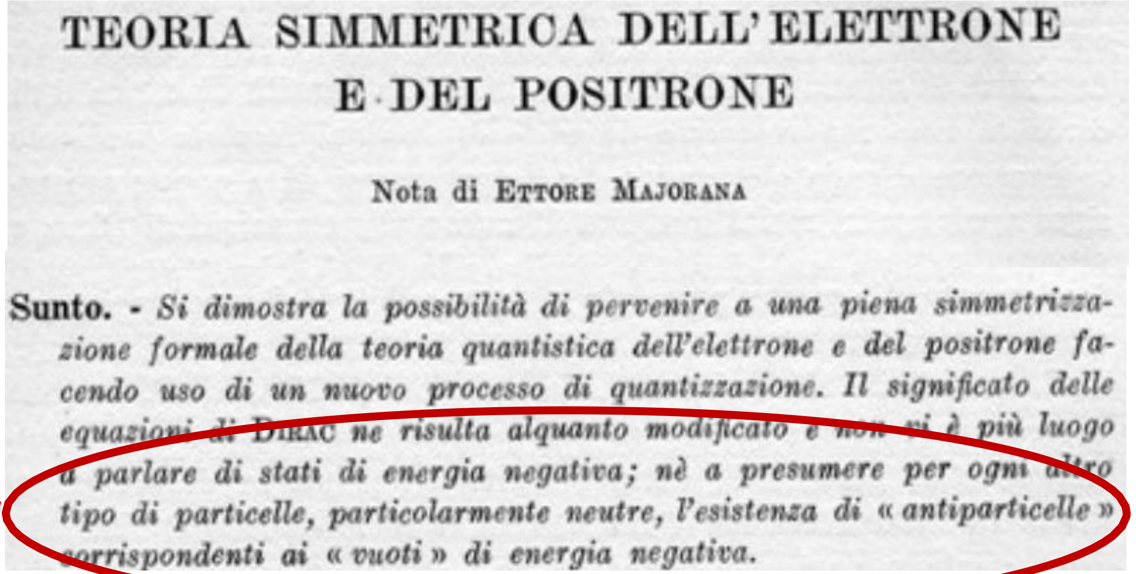
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \quad 2\nu2\beta$$

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

Nuovo Cimento 14(1937)171-184

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

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

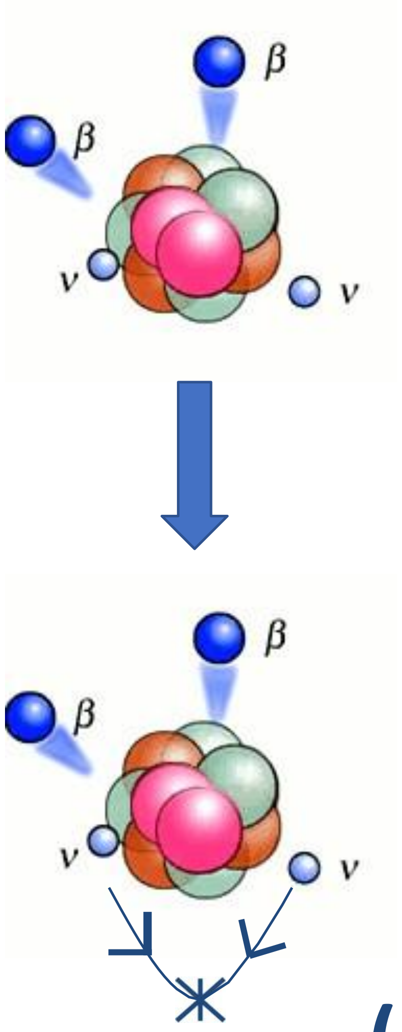


TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

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

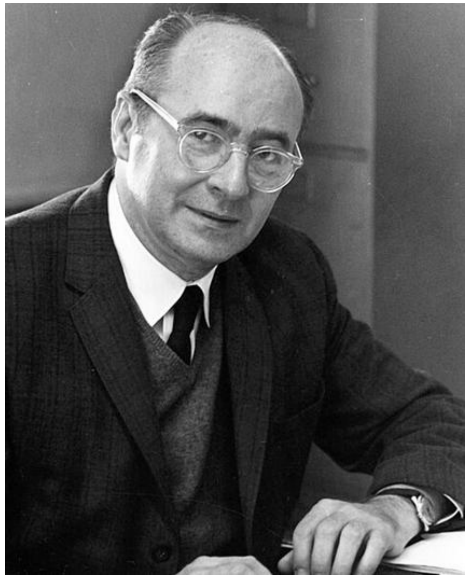


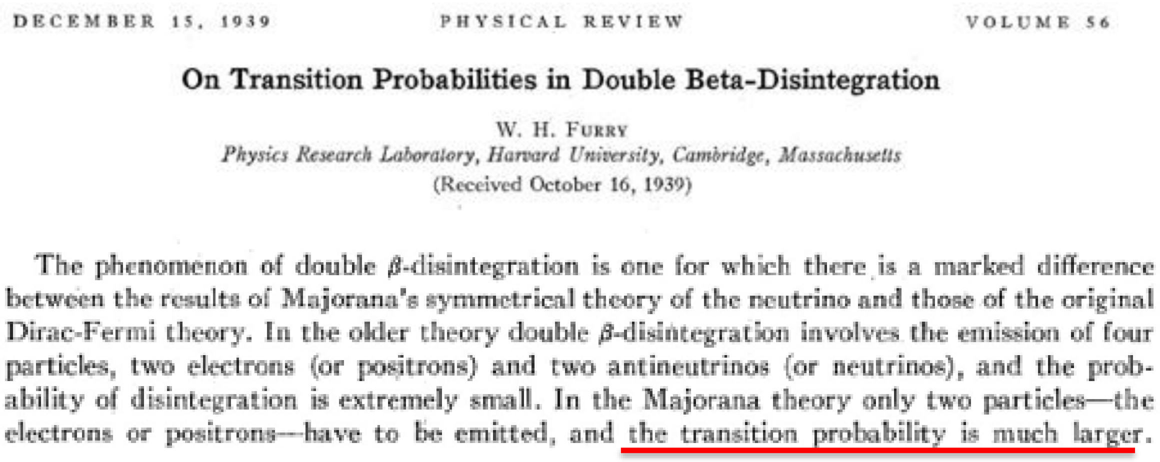
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ $2\nu2\beta$

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

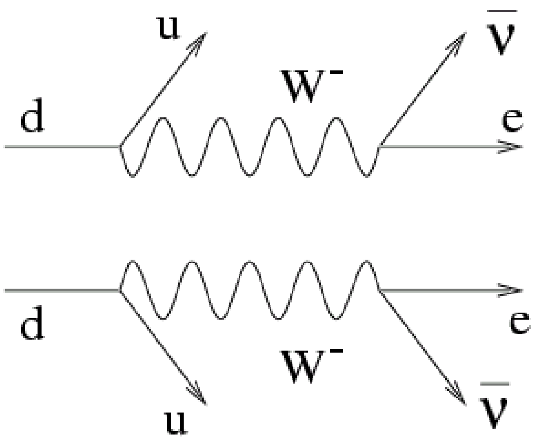
$(A,Z) \rightarrow (A,Z+2) + 2e^-$ $0\nu2\beta$

Violation of lepton number

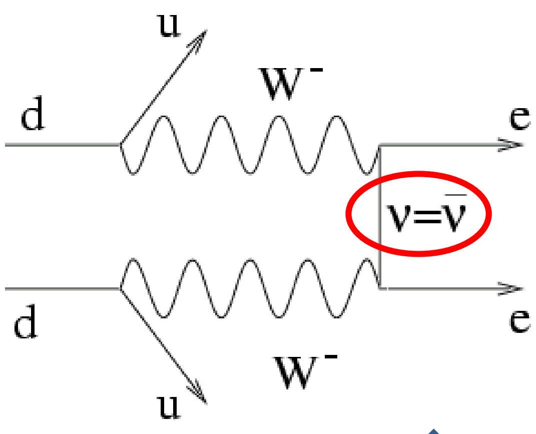
$\Delta L = 2$

Double beta decay and neutrino physics

Two diagrams can be drawn to represent the two types of double beta decays



$2\nu2\beta$
Standard-Model allowed process
two "simultaneous" beta decays



$0\nu2\beta$
A **virtual neutrino** is exchanged
between the two electroweak lepton vertices

Neutrino flavor oscillations

Claudio Giganti
This school

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

Flavor eigenstates $\neq$ Mass eigenstates

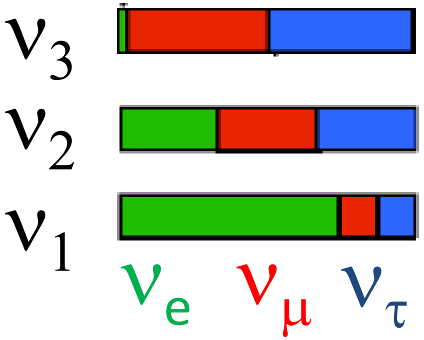
Weak interaction — Propagation

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \begin{matrix} M_1 \\ M_2 \\ M_3 \end{matrix}$$

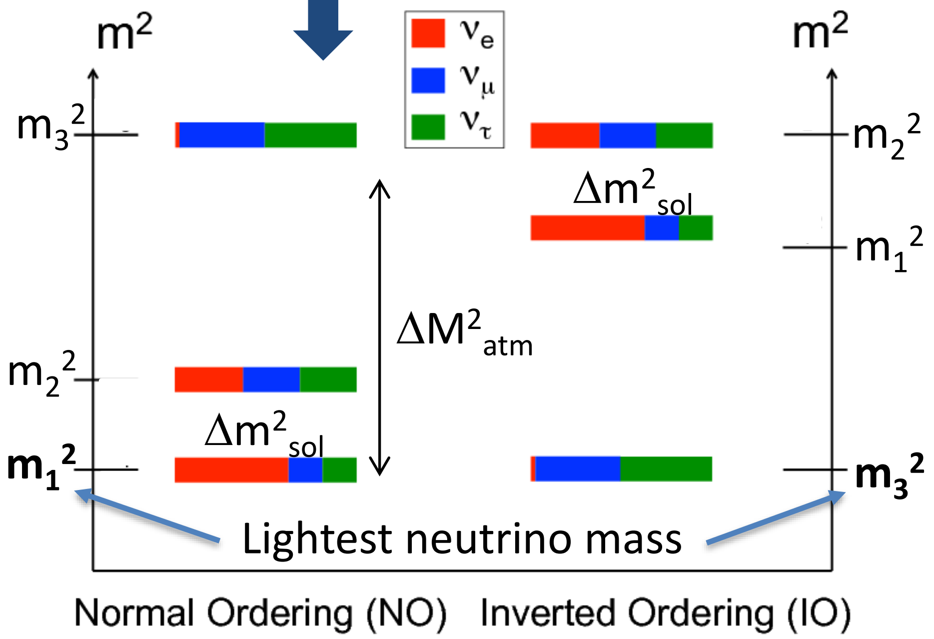
Neutrino flavor oscillations

Neutrino mixing matrix (PMNS)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



Neutrino mass ordering

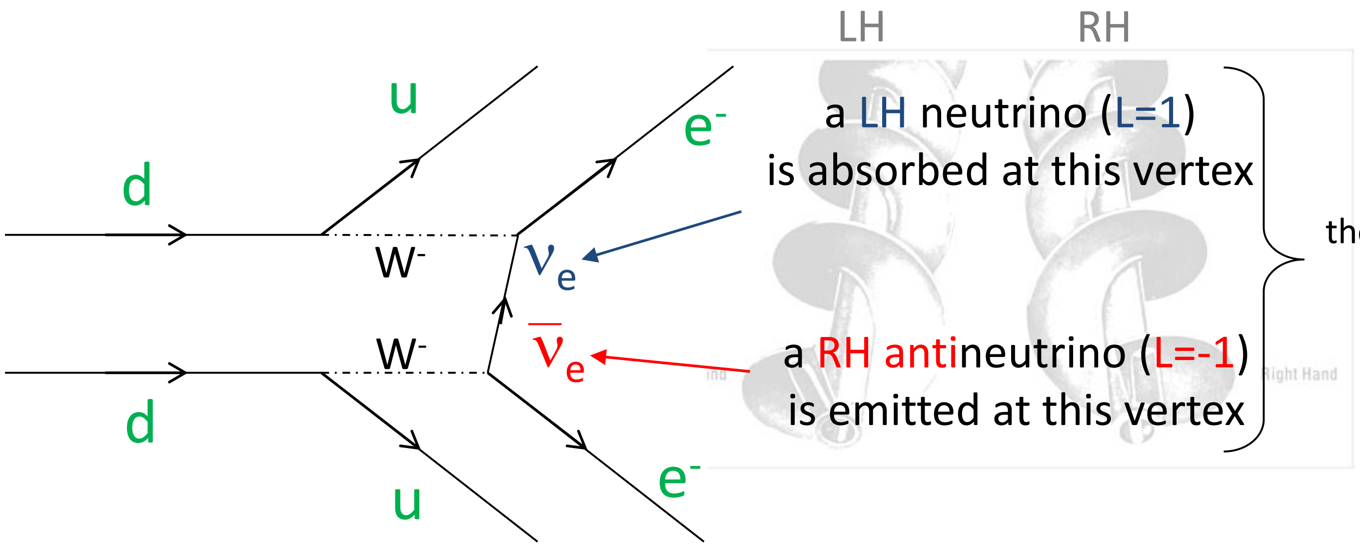


$\Delta m_{sol}^2 \sim (9\ \text{meV})^2$
Solar

$|\Delta m_{atm}^2| \sim (50\ \text{meV})^2$
Atmospheric

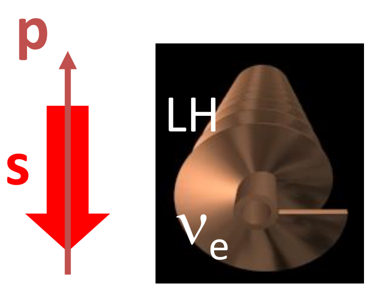
At least two neutrino masses are not vanishing

Double beta decay and neutrino physics

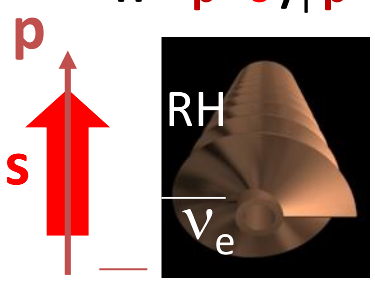


in pre-oscillations Standard Model (massless neutrinos), the process is forbidden because neutrino has not the correct **helicity / lepton number** to be absorbed at the second vertex

Goldhaber experiment
Maximal parity violation



H = p · s /| p · s |



If $m_\nu \neq 0$, a RH neutrino has a small component of negative helicity H

$A(H=-1) \propto m_\nu / E_\nu$

$\bar{\nu} = \nu$

- IF neutrinos are massive MAJORANA particles:

  Helicities can be accommodated thanks to the **finite mass**, **AND** Lepton number is not relevant

  → **0ν-DBD is allowed**

$\bar{\nu} \neq \nu$

- IF neutrinos are massive DIRAC particles:

  Helicities can be accommodated thanks to the **finite mass**, **BUT** Lepton number is rigorously conserved

  → **0ν-DBD is forbidden**

If neutrinos are massless, the Dirac and Majorana descriptions degenerate, and neutrinoless double beta decay is forbidden

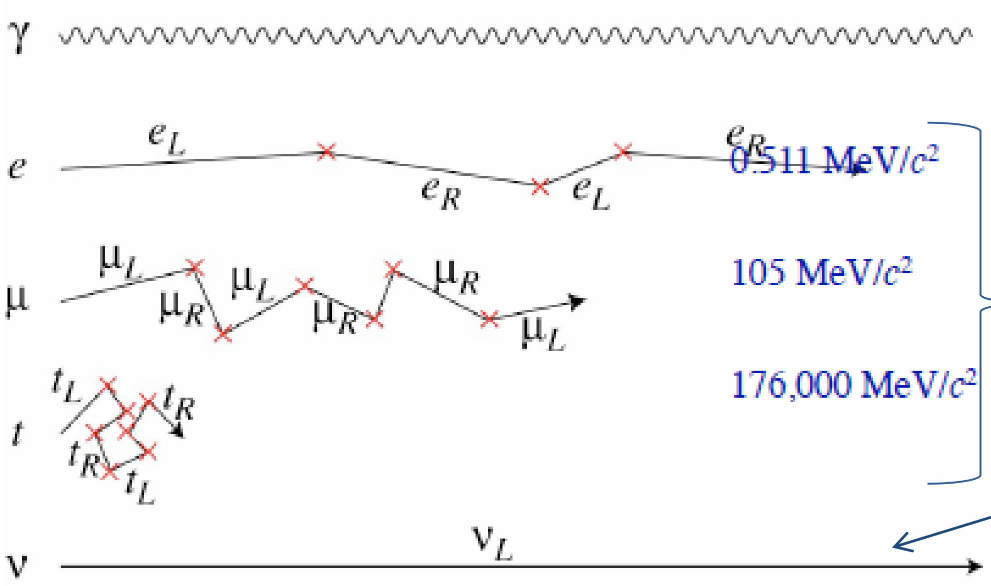
In the Standard Model, neutrinos are massless

Origin of the charged fermion masses in the Standard Model

$$\mathscr{L}_{\text{Yukawa}} = -\frac{\lambda v}{\sqrt{2}}(\overline{l_L} l_R + \overline{l_R} l_L)$$

Particles

M



Photons do not have a mass because they do not interact with the Higgs field

Charged fermions acquire a mass by bumping on the Higgs field which pervades all the empty space and connects left- and right-handed components

Neutrinos do not have a mass because they do not have a right-handed component and the left-handed component propagate freely

Giving masses to neutrinos

Follow what is done with the other fermions in a straight-forward way

Dirac mass

$$\mathscr{L}_D = -m_D(\overline{\nu_L}\nu_R + \text{h.c.})$$

where $\boldsymbol{\nu}_\mathbf{R}$ are new fields insensitive to the gauge interactions

However, we are authorised to add a new mass term **only for neutrinos**

Majorana mass

$$\mathscr{L}_M = -\frac{1}{2}M_R(\bar{\nu}_R^C\nu_R + \text{h.c.})$$

which involves fields of equal chiralities
possible only for neutral particles!

Giving masses to neutrinos

In matrix notation:

$$\mathscr{L}_{D+M} = -\frac{1}{2} N_L^T \mathscr{C}^\dagger M N_L + \text{h.c.} \qquad N_L = (\nu_L, \nu_R^C)$$

Provides the Dirac and Majorana mass terms defined before

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & m_D \\ \nu_R & m_D & M_R \end{array} \qquad M = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

In order to find the physical states and masses, this matrix must be diagonalized to put the Lagrangian in the form:

$$\mathscr{L}_{D+M} = \sum_i m_i \overline{\nu}_i \nu_i$$

See-saw mechanism

After diagonalization:

Eigenvalues

$$m \sim m_D \cdot (m_D / M_R)$$

$$m_N \sim M_R + m$$

Light Majorana neutrinos ⇒ **Those that undergo flavor oscillations and mediate 0ν2β**

Eigenvectors
(Majorana particles!)

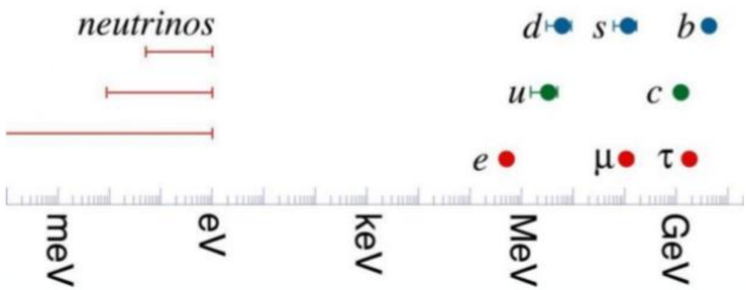
$$\nu \sim \nu_L + \nu_L^c - (m_D / M_R)(\nu_R + \nu_R^c)$$

$$N \sim \nu_R + \nu_R^c + (m_D / M_R)(\nu_L + \nu_L^c)$$

$$m << m_N$$

Heavy Majorana neutrinos, usually indicated with **N** → **Leptogenesis (asymmetry matter / anti-matter)**

- $\mathbf{m_D}$ must be of the same order of the charged lepton masses (Higgs mechanism)
- $\mathbf{M_R}$ can be everywhere (up to the GUT scale)
  → the condition $\mathbf{M_R >> m_D}$ naturally explains the small neutrino masses



Leptogenesis

If there is a source of CP violation in the lepton sector (δ or Majorana phases), the heavy Majorana neutrinos *N* can violate CP too and decay with different rates to e^+ and e^-

Different rates →

$$N \rightarrow e^- + H^+ \quad \text{and} \quad N \rightarrow e^+ + H^-$$

Standard-Model Higgs

Unequal number of leptons and anti-leptons in the early Universe

Sphaleron process (violate B and L, but conserves B-L)

The asymmetry is transferred to baryons

Effective field theory

Hypothesis: the Standard Model is the low-energy limit of a more general theory

Construct an **Effective Field Theory (EFT)**, introducing a high-energy cut-off scale Λ

Lagrangian is expanded in powers of 1/ Λ, using only Standard Model fields and respecting all its symmetries

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + \ldots$$

Dim 4 Dim 5 Dim 6

Leptons Higgs

Only one Dim 5 operator

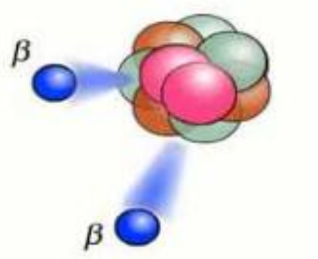
$$\mathcal{O}^{(5)} = (\bar{L}_L\tilde{\phi})(\tilde{\phi}^\dagger L_L^c)$$

$$(1/\Lambda)\,(L\langle H\rangle)\,(L\langle H\rangle) = (\langle H\rangle^2/\Lambda)\,\nu\,\nu = m\,\nu\,\nu$$

Majorana mass term

Standard and non-standard mechanisms for $0\nu 2\beta$

$0\nu 2\beta$ is a test for « creation of leptons »: **$2n \rightarrow 2p + 2e^-$** $\Rightarrow$ **LNV**



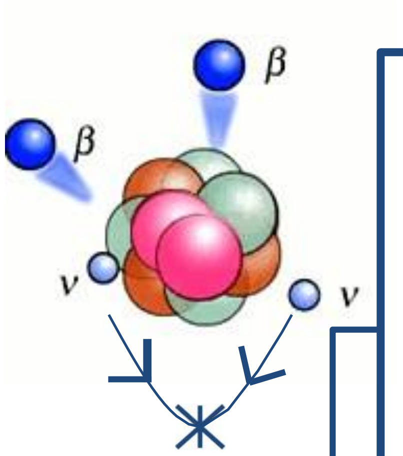
This test is implemented in the nuclear matter:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$

$0\nu 2\beta$

Standard mechanism: **neutrino physics**
$0\nu 2\beta$ is mediated by **light massive Majorana neutrinos**
(ordinary neutrinos, exactly those which oscillate)

Non-standard mechanism (**not necessarily neutrino physics**)
- Exchange of heavy Majorana neutrinos
- Light massive sterile ν states
- Right-hand currents
- Supersymmetry
- Exotic particles (leptoquarks,…) or operators (dim 7, dim 9)

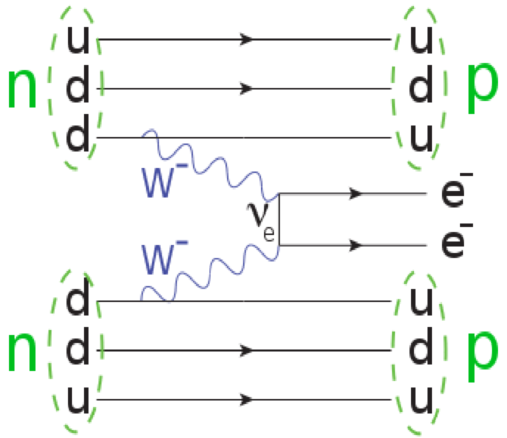
$0\nu2\beta$: the mass mechanism



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

- Elements of the neutrino PMNS mixing matrix (first row)
- Three neutrino masses (connected by Δm^2_{ij})

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

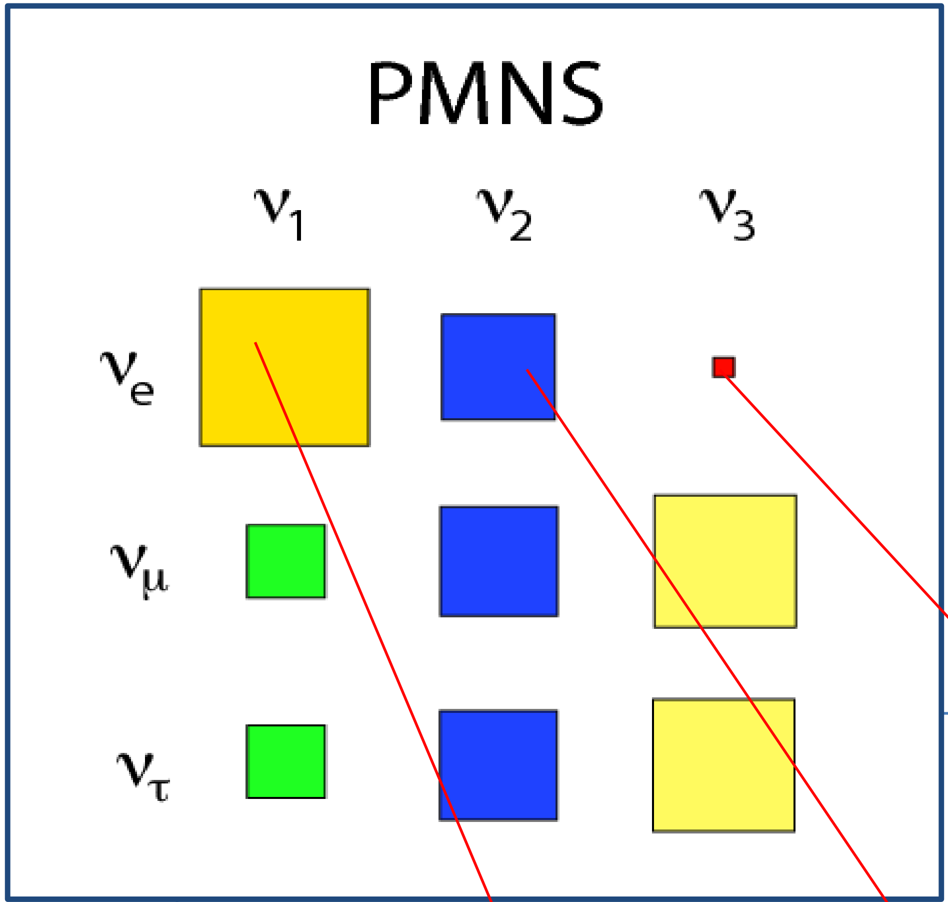
parameter containing neutrino physics: **Effective Majorana mass**

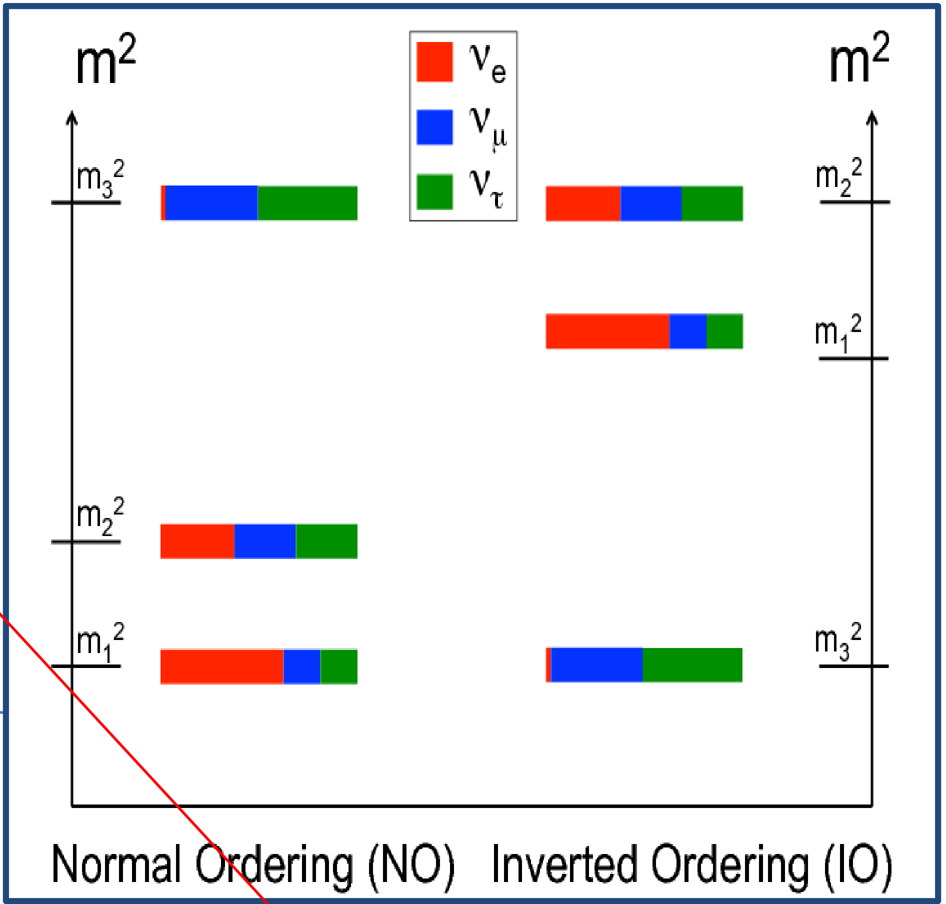
Masses appear to accommodate helicities

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

α_i
Majorana phases

Light Majorana neutrino exchange: the rate formula



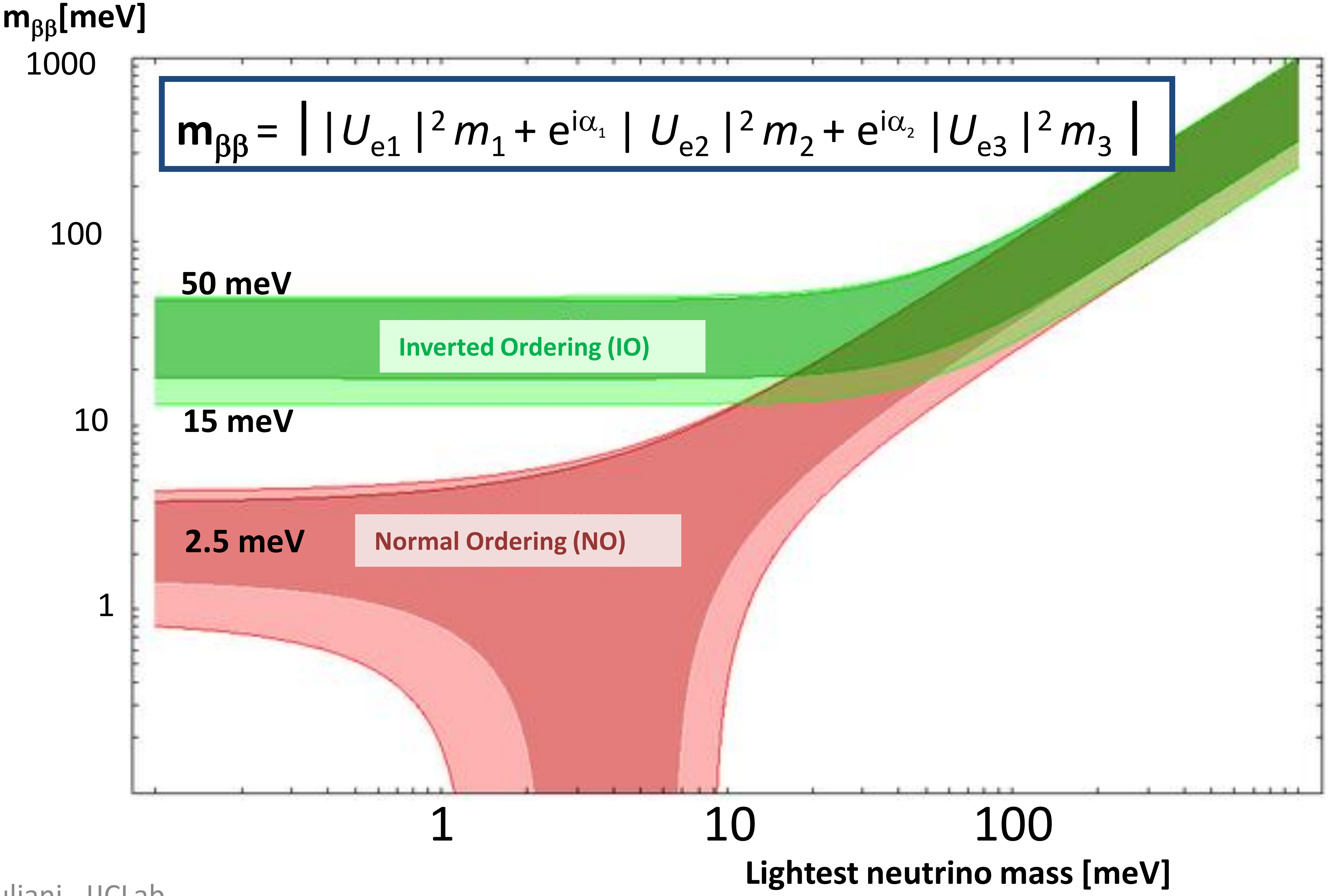


Masses appear to accommodate helicities

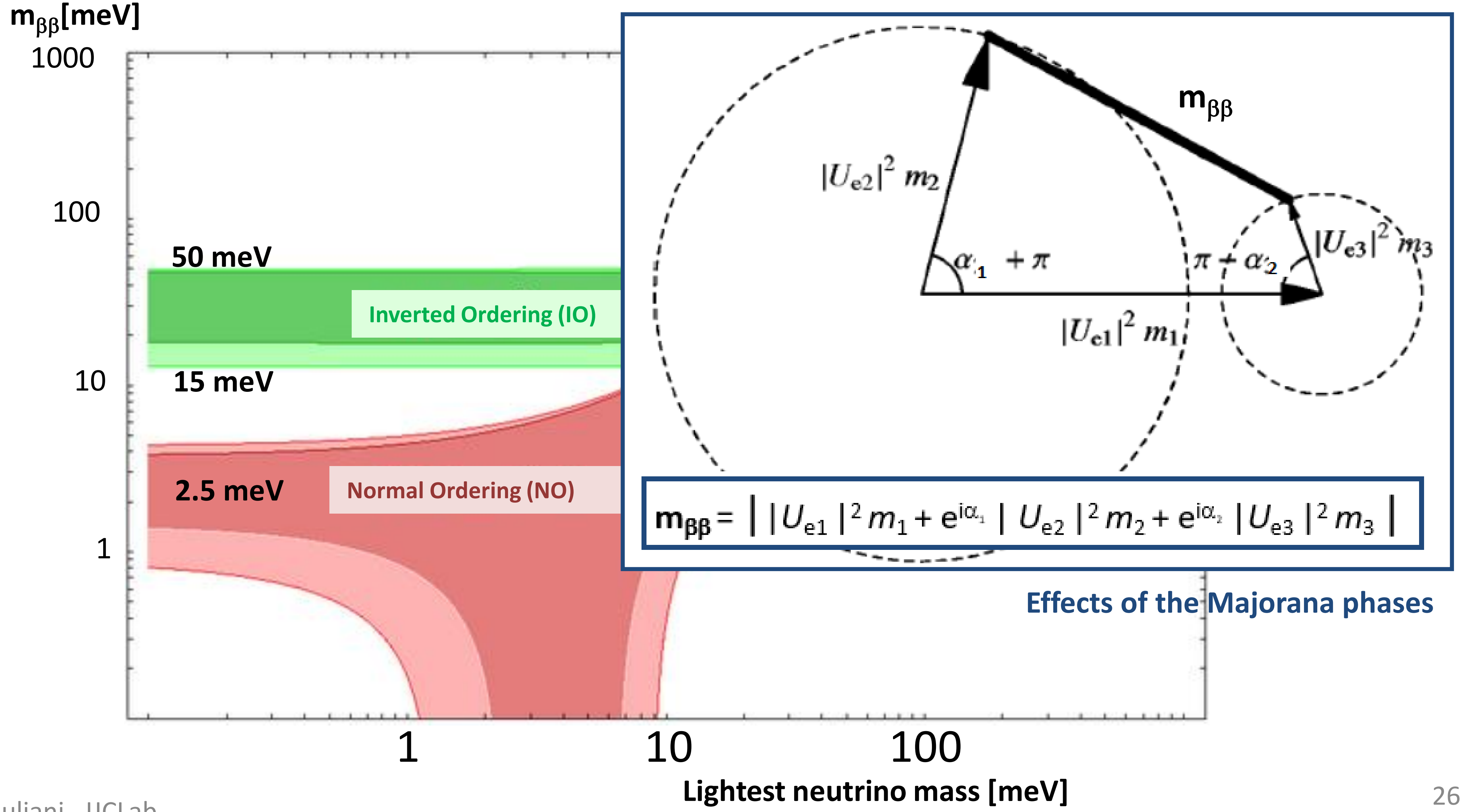
$$m_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

α_i Majorana phases

$m_{\beta\beta}$ as a function of the lightest neutrino mass

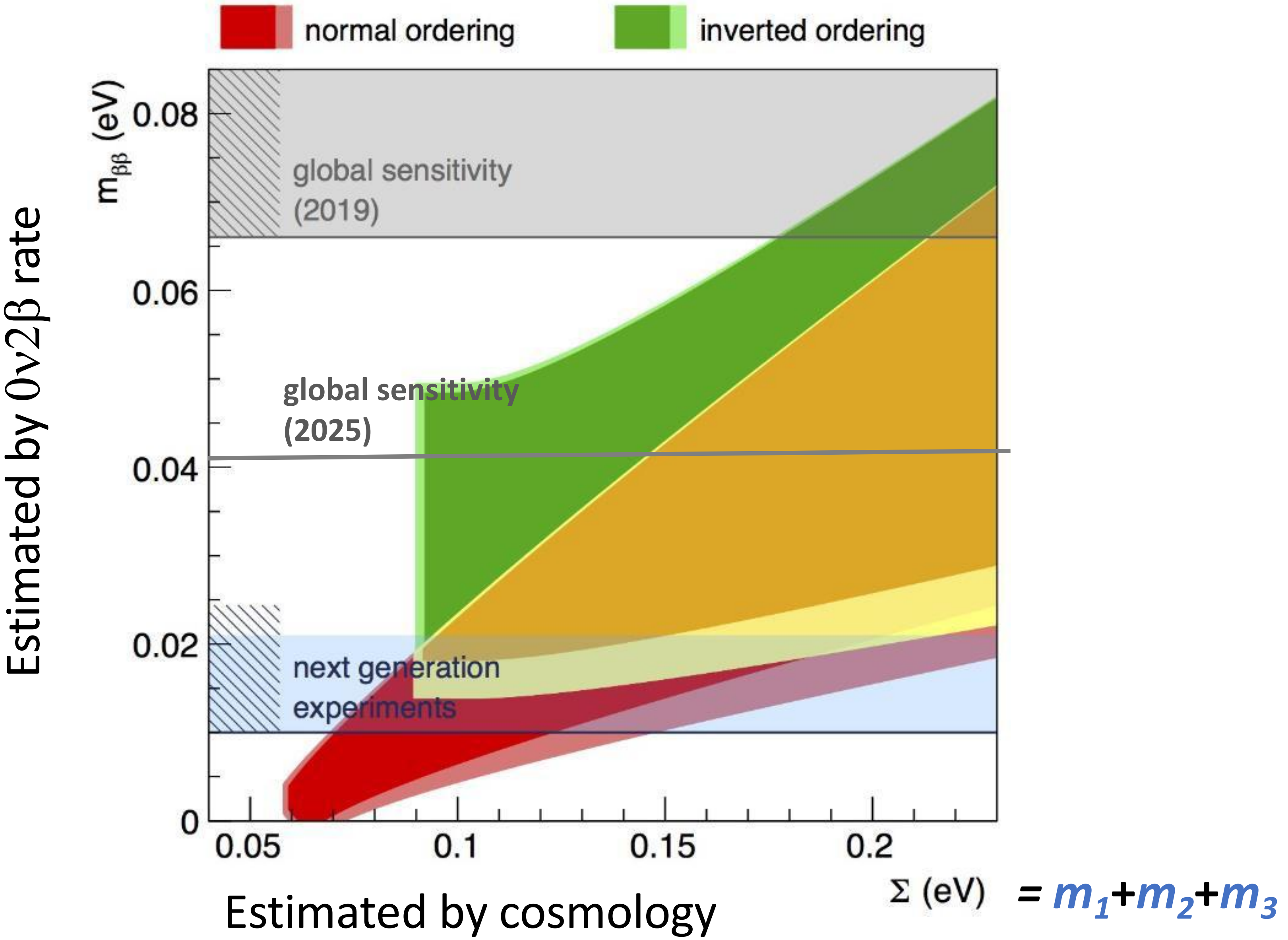


$m_{\beta\beta}$ as a function of the lightest neutrino mass



Effects of the Majorana phases

$m_{\beta\beta}$ as a function of the sum of the three neutrino masses



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**

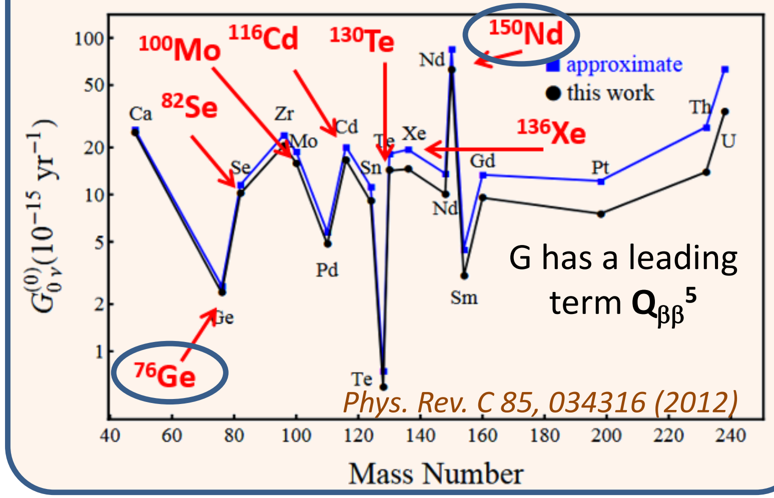
Outline

1. Double beta decay and physics beyond the Standard Model
2. **Experimental challenge and state-of-the-art**
3. The bolometric technique: principle and experiments

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



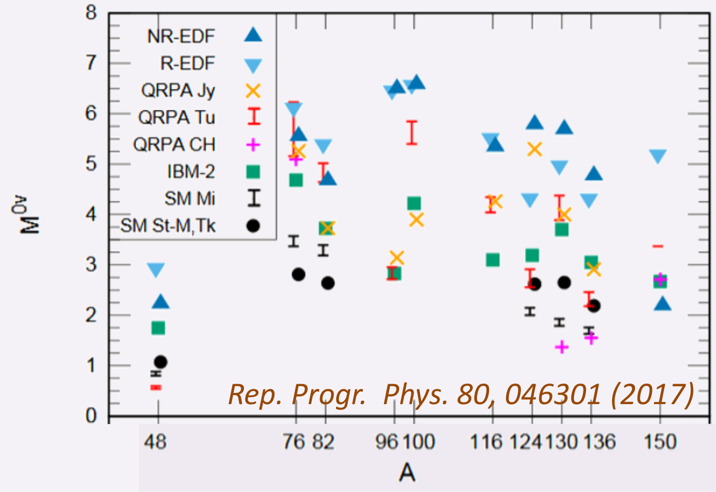
Phys. Rev. C 85, 034316 (2012)

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

$g_{A,eff}$ ~ **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



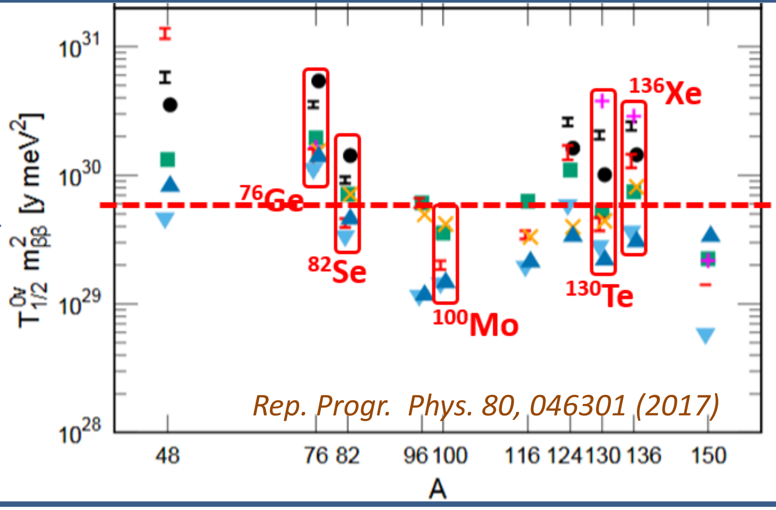
Rep. Progr. Phys. 80, 046301 (2017)

0νββ rate

The 0νββ community still assumes **$g_A \approx 1.27$** (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

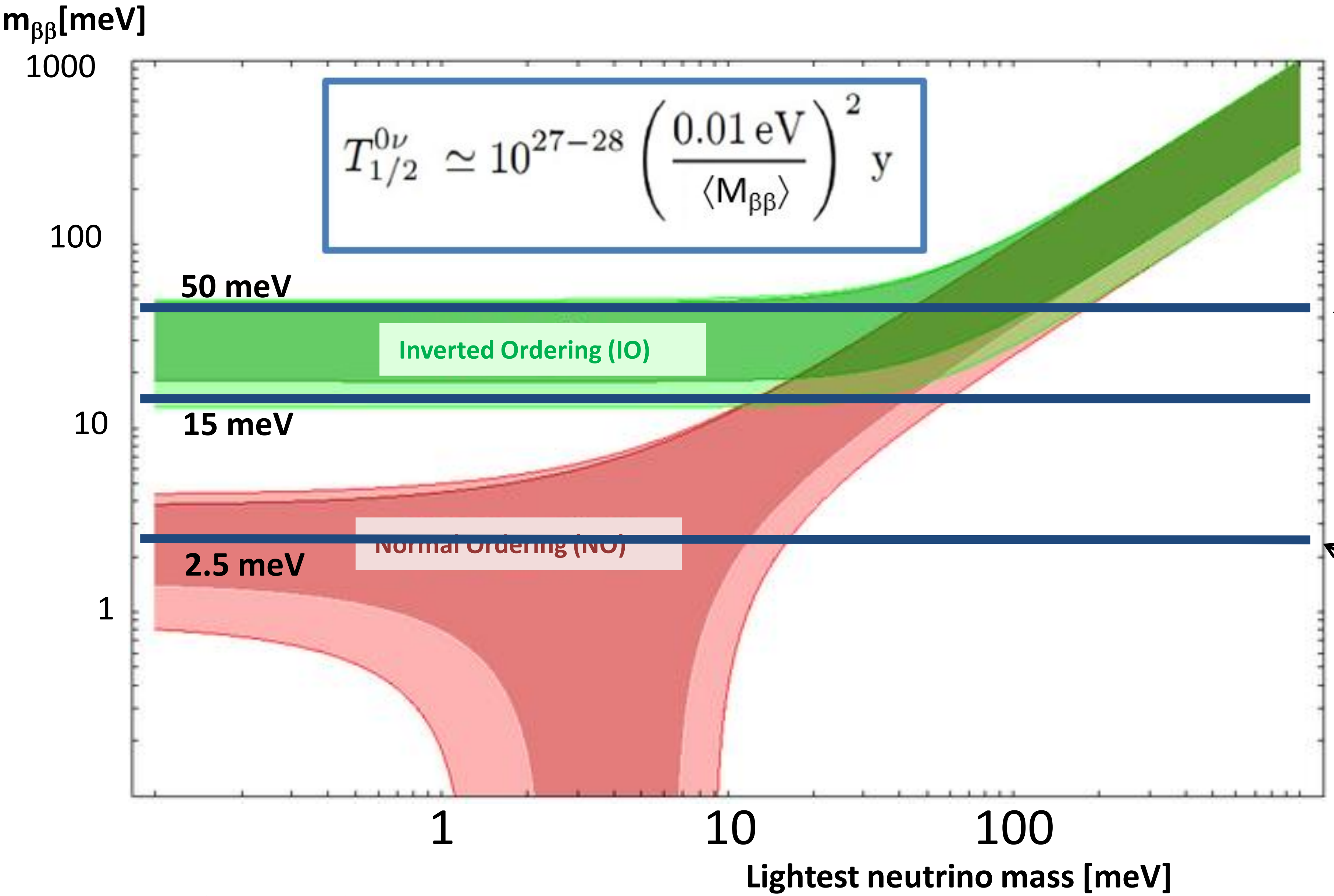


Rep. Progr. Phys. 80, 046301 (2017)

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

Working formula for general experiment design

The experimental challenge

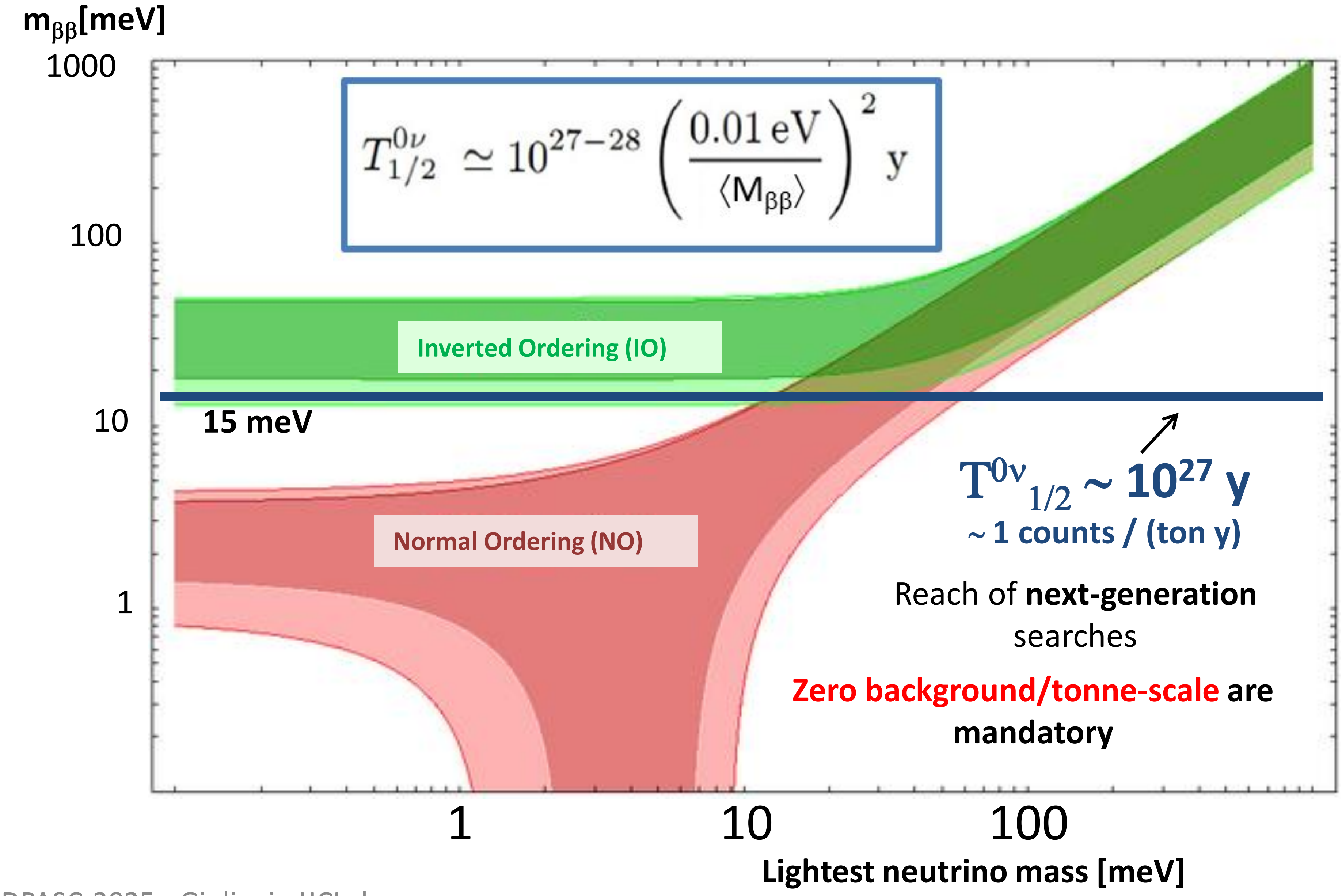


$T^{0\nu}_{1/2} \sim 10^{26}$ y
~ 10 counts / (ton y)
Reach of the **current** searches

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

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

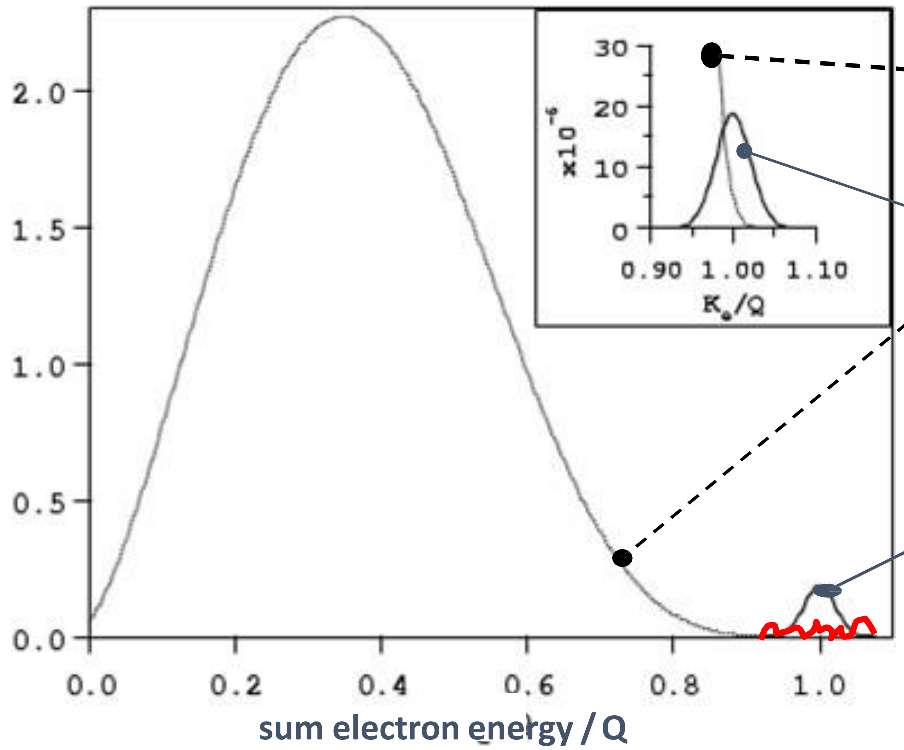
Zero background

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

$$F \propto MT$$

Searching for 0ν2β

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

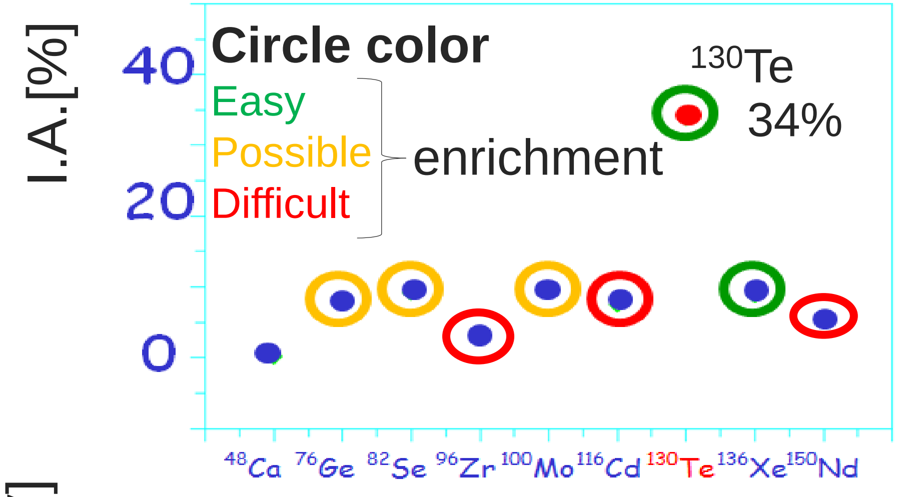
Backround index BI
counts/(keV kg y)

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

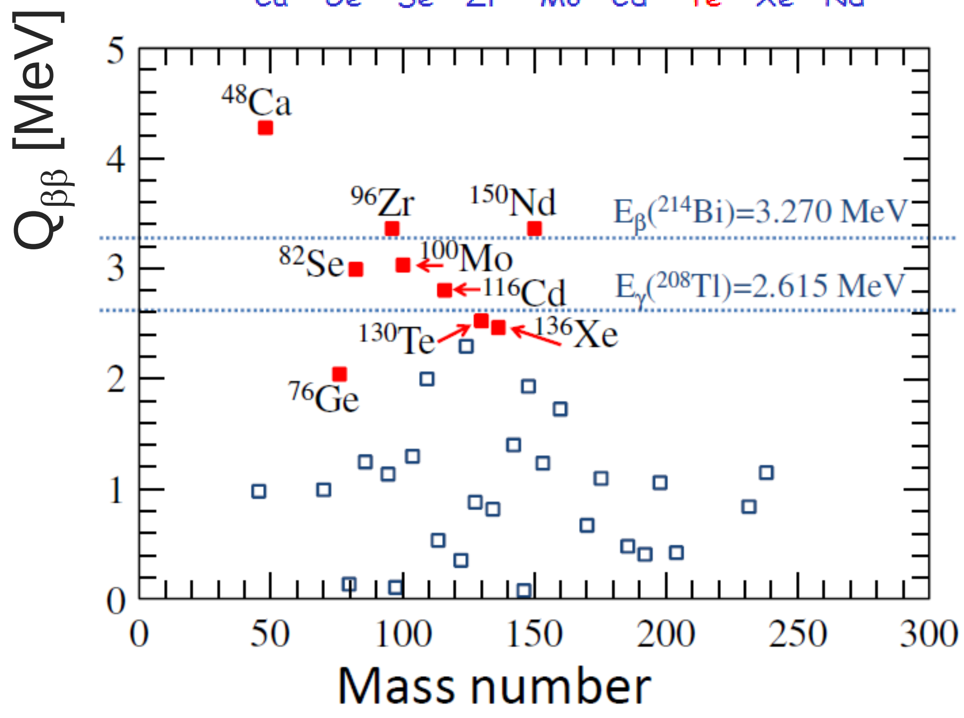
- **High isotopic abundance** (I.A.) and/or **easy enrichment**



- **High $Q_{\beta\beta}$**

Larger phase space: G(Q,Z) ∝ Q^5

Easier background control



Compatibility with a beneficial **detection technique**

High energy resolution

Background identification

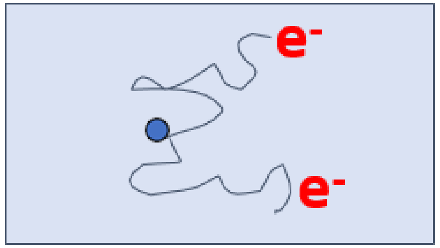
Efficiency and scalability

Searching for $0\nu2\beta$

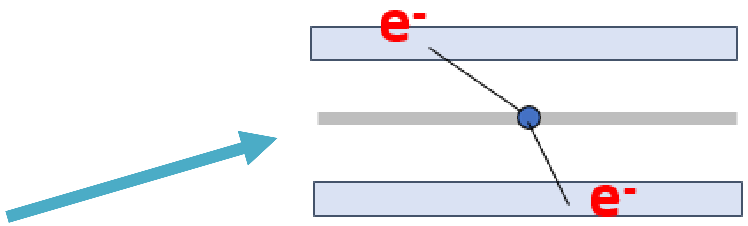
Requests for the source

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

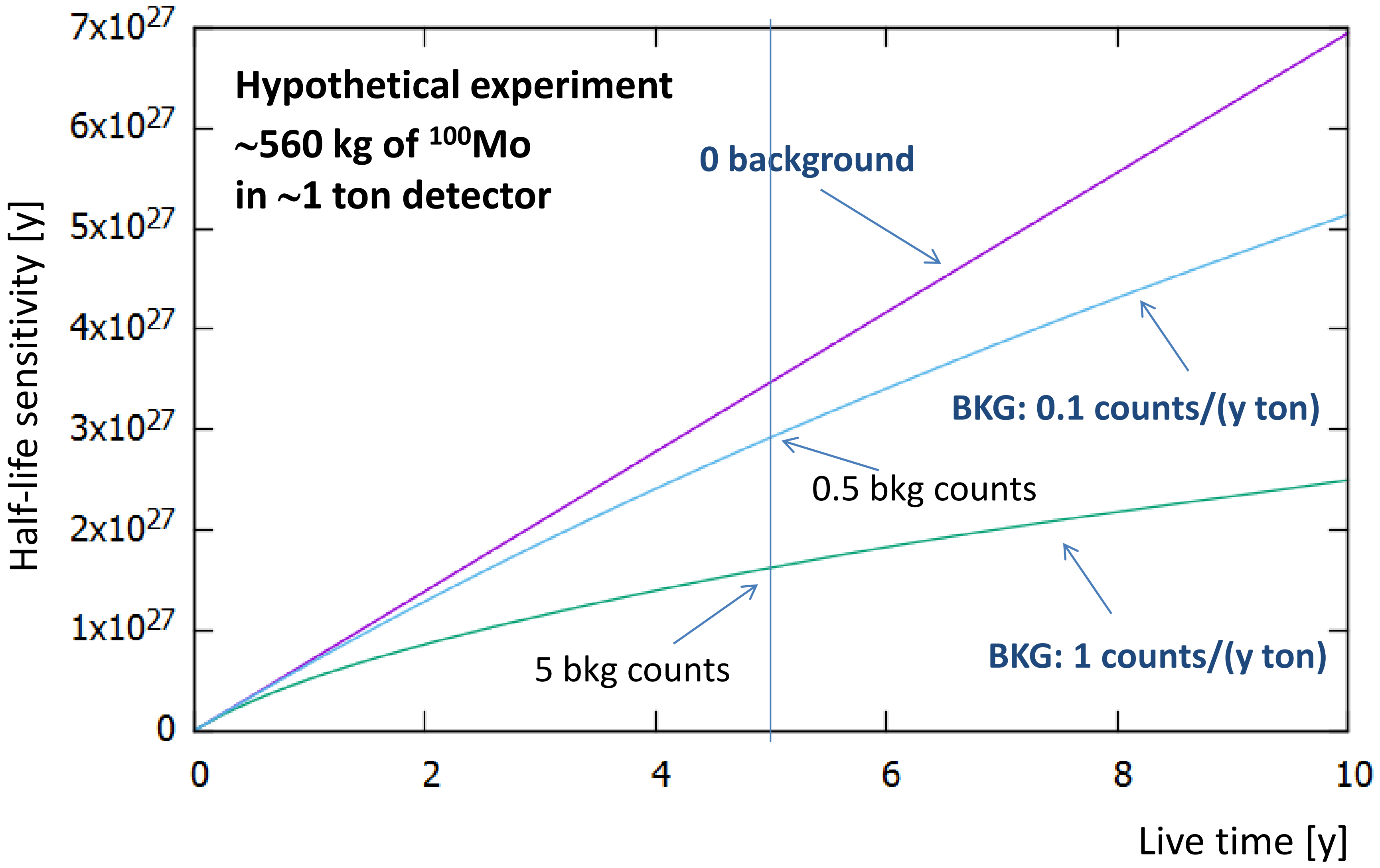
Requests for the background

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

Effect of the background on the sensitivity



Searching for 0ν2β: 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

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

① **Source dilution in a liquid scintillator**

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

② **TPCs**

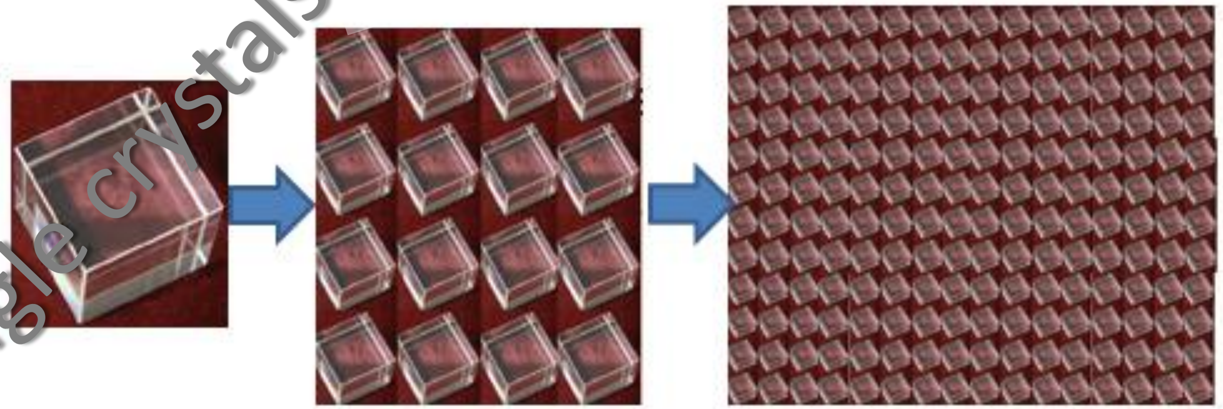
EXO-200 – NEXT – nEXO (^{136}Xe)

③ **Semiconductor detectors**

GERDA – LEGEND (^{76}Ge)

④ **Bolometers**

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



l)
on
FWHM

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

① **Source dilution in a liquid scintillator**

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

② **TPCs**

EXO-200 – NEXT – nEXO (^{136}Xe)

③ **Semiconductor detectors**

GERDA – LEGEND (^{76}Ge)

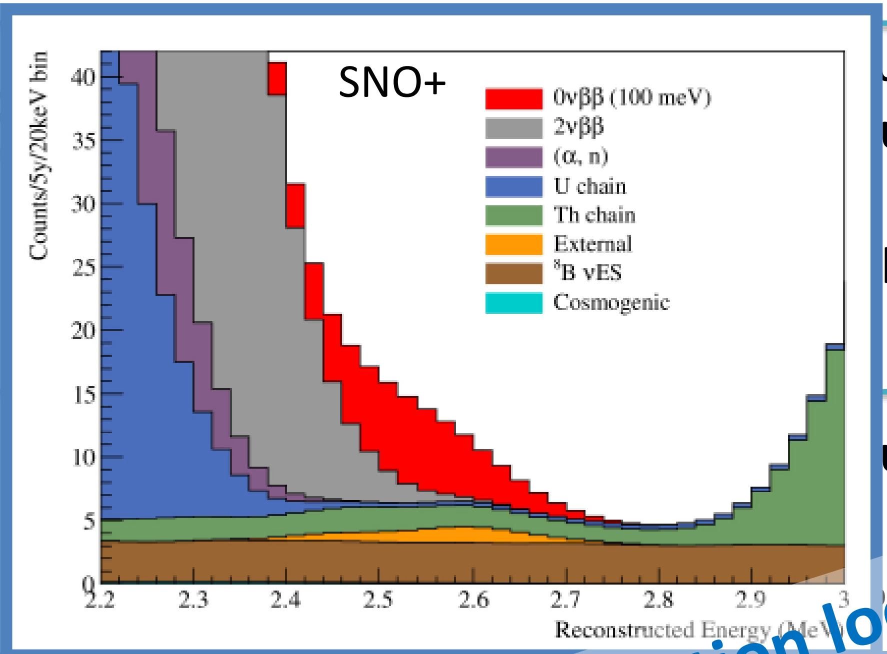
④ **Bolometers**

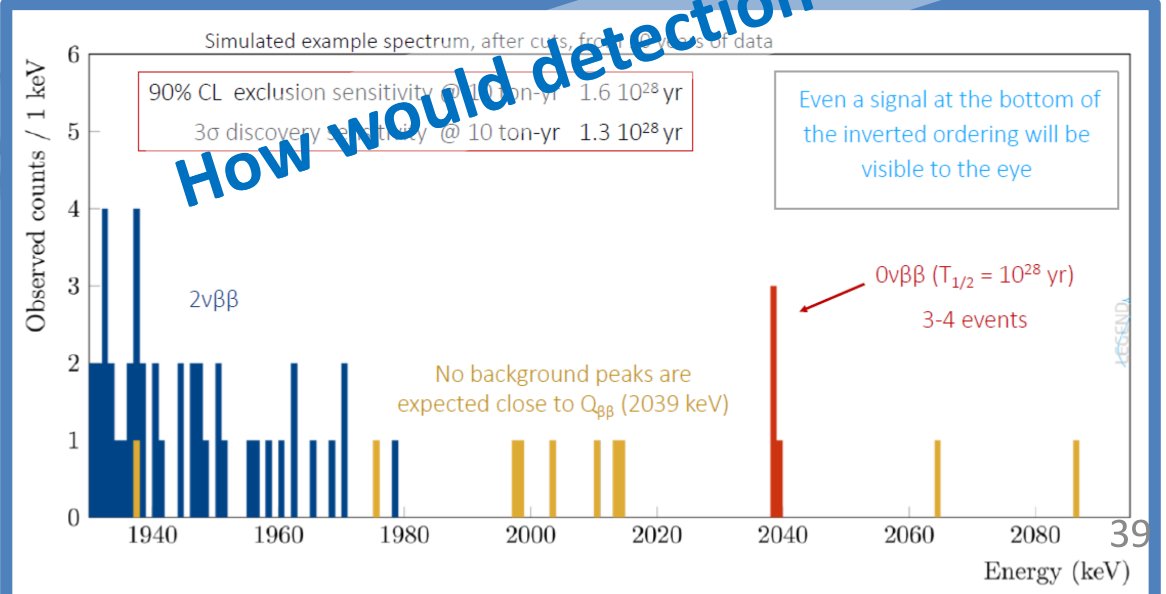
CUORE (^{130}Te) – AMoRE – CUPID (^{100}Mo)

Liquids and gases

Single crystals

ures
ulti-ton)
HM
ulti-ton)
FWHM





How would detection look like?

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)

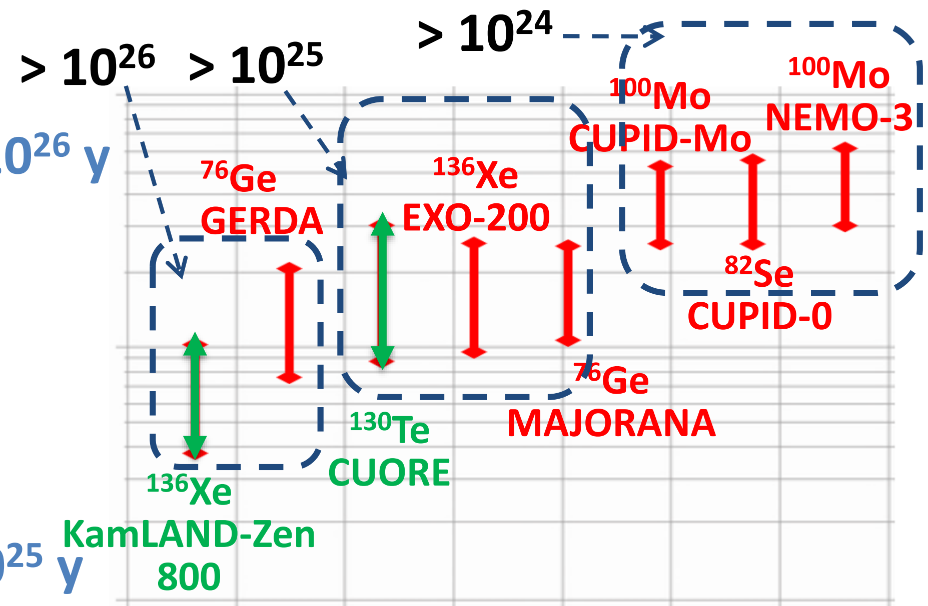
MAJORANA dem. - $T_{1/2} > 8.3\times10^{25}$ y
Phys. Rev. Lett. 130, 062501 (2023)

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

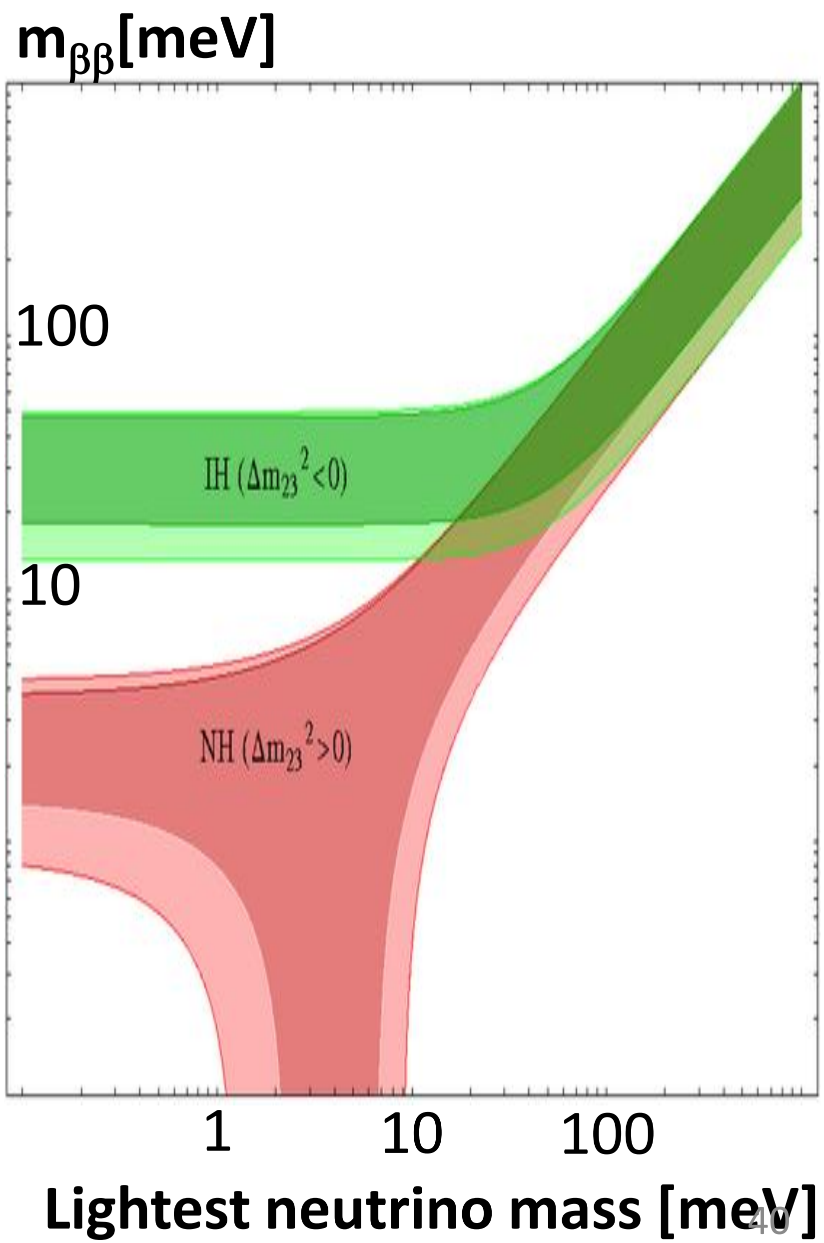
CUPID-0 - $T_{1/2} > 4.6\times10^{24}$ y
Phys. Rev. Lett. 129, 111801 (2022)

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**

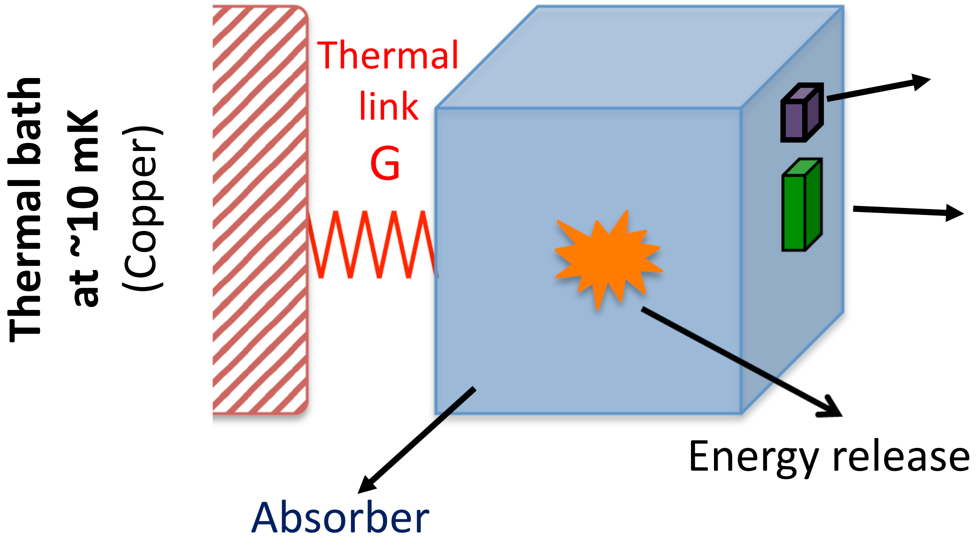
Outline

1. Double beta decay and physics beyond the Standard Model

2. Experimental challenge and state-of-the-art

3. **The bolometric technique: principle and experiments**

Bolometric technique

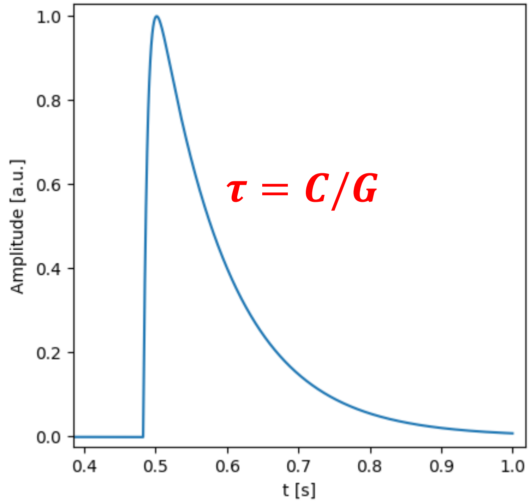


Heater:
For correction of temperature instabilities

Temperature sensor:
Neutron Transmutation Doped (NTD) Germanium thermistor

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

$\Delta T \rightarrow \Delta R$
$R(T) = R_0 \cdot e^{\sqrt{T_0/T}}$



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

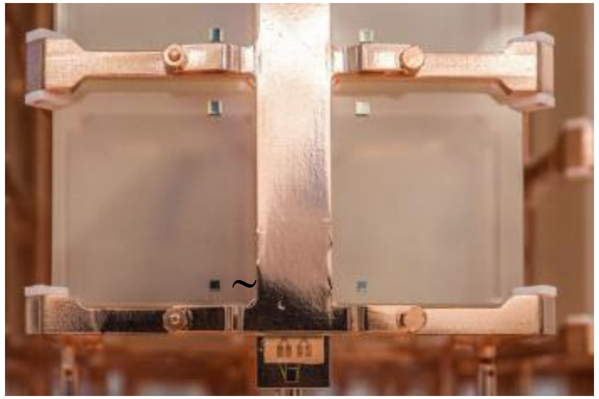
CUORE in a nutshell

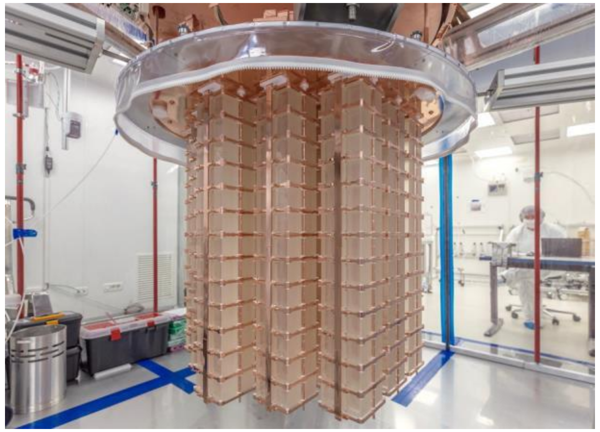
CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy) at ~**12-15 mK**

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**)
- 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)

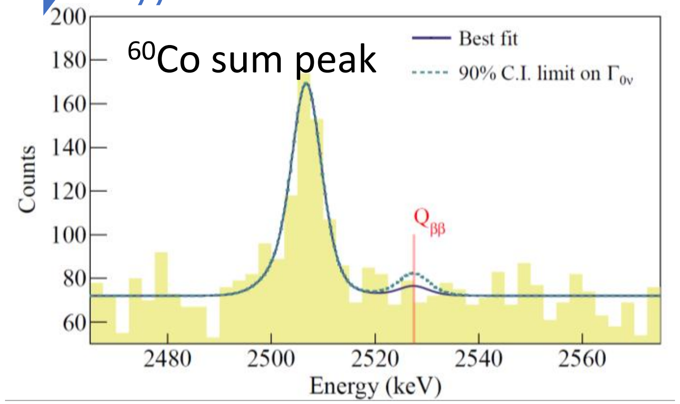




One of the most sensitive $0\nu2\beta$ experiments of the current generation

- 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**

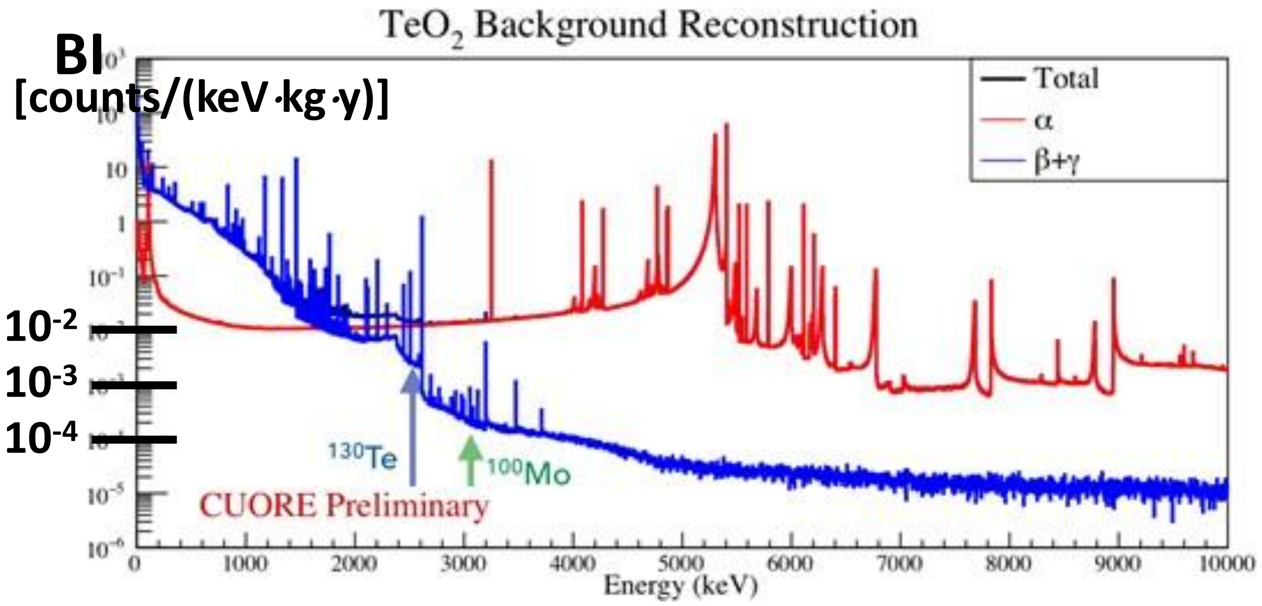
CUORE → CUPID

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**

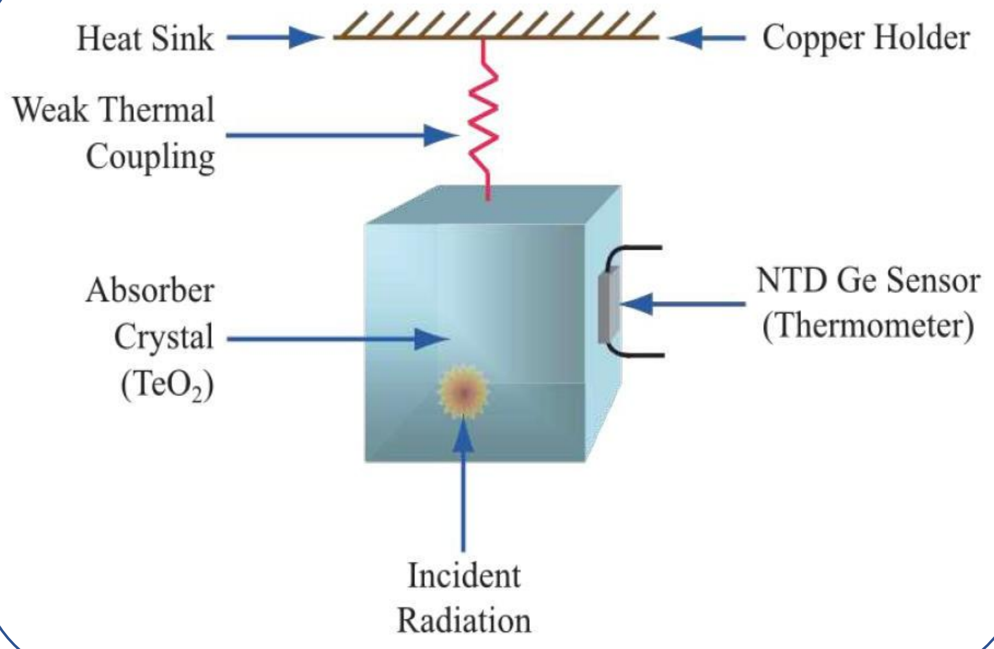
CUORE background model



- 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

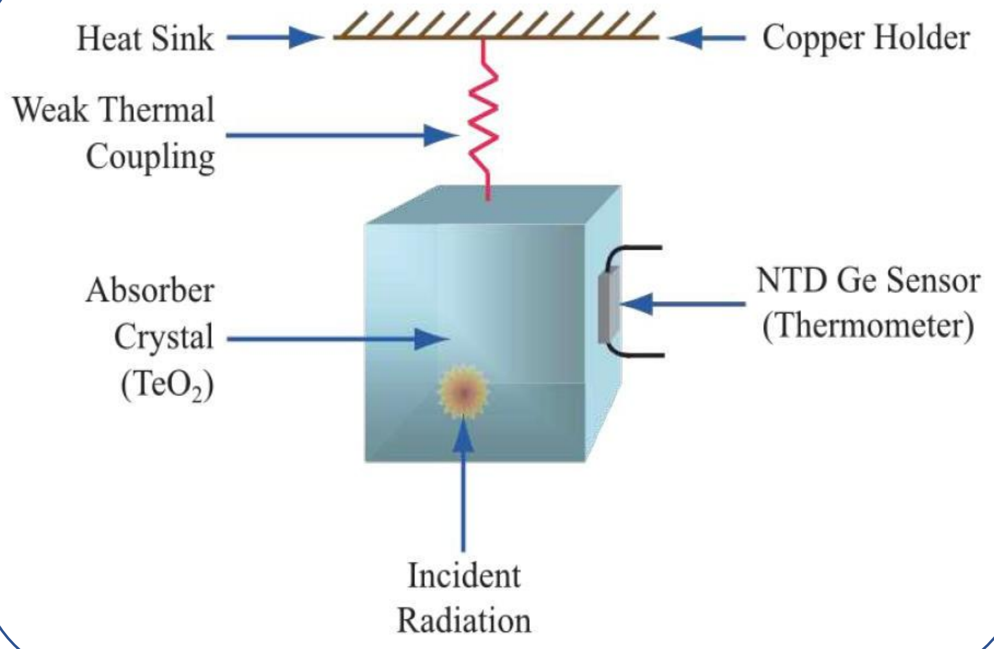
CUORE ^{130}Te
pure thermal detector
(**bolometer**)



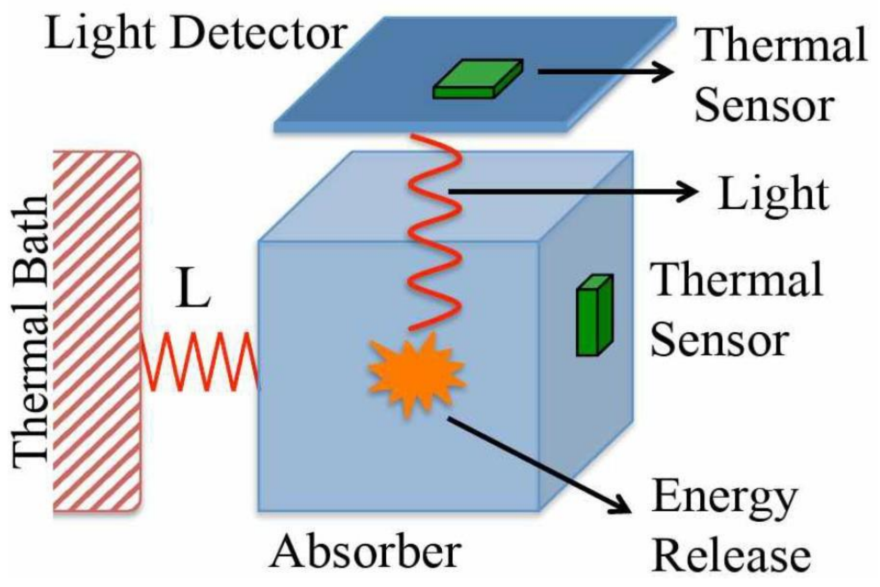
No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

CUPID rationale

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



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



No PID

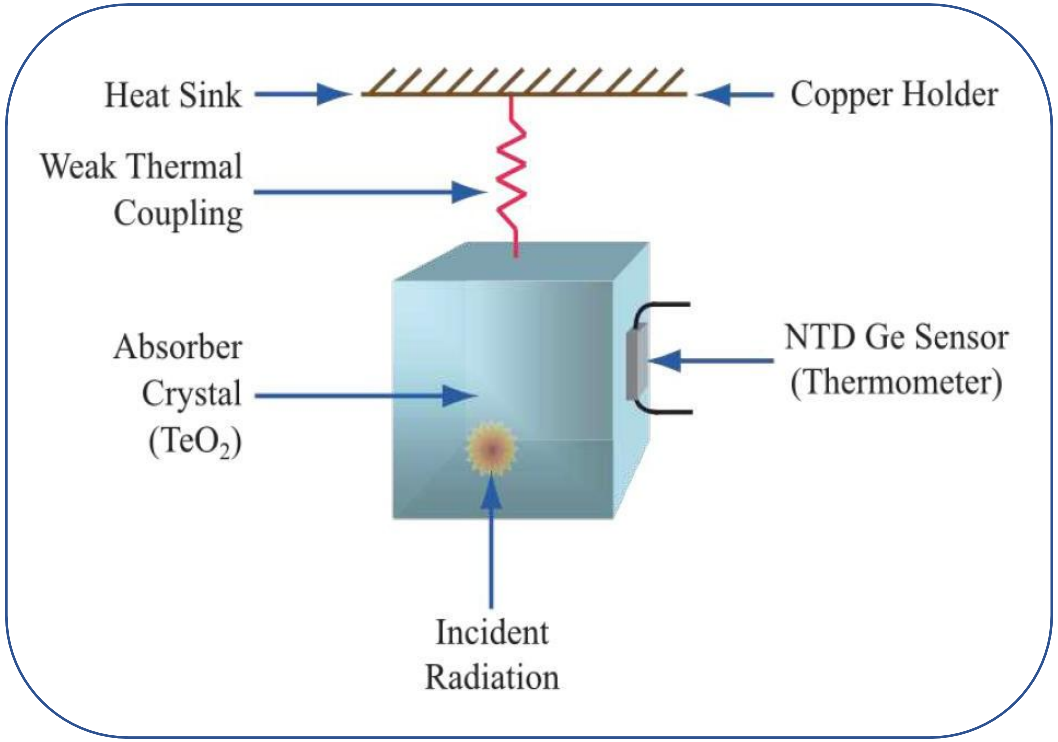
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

α background

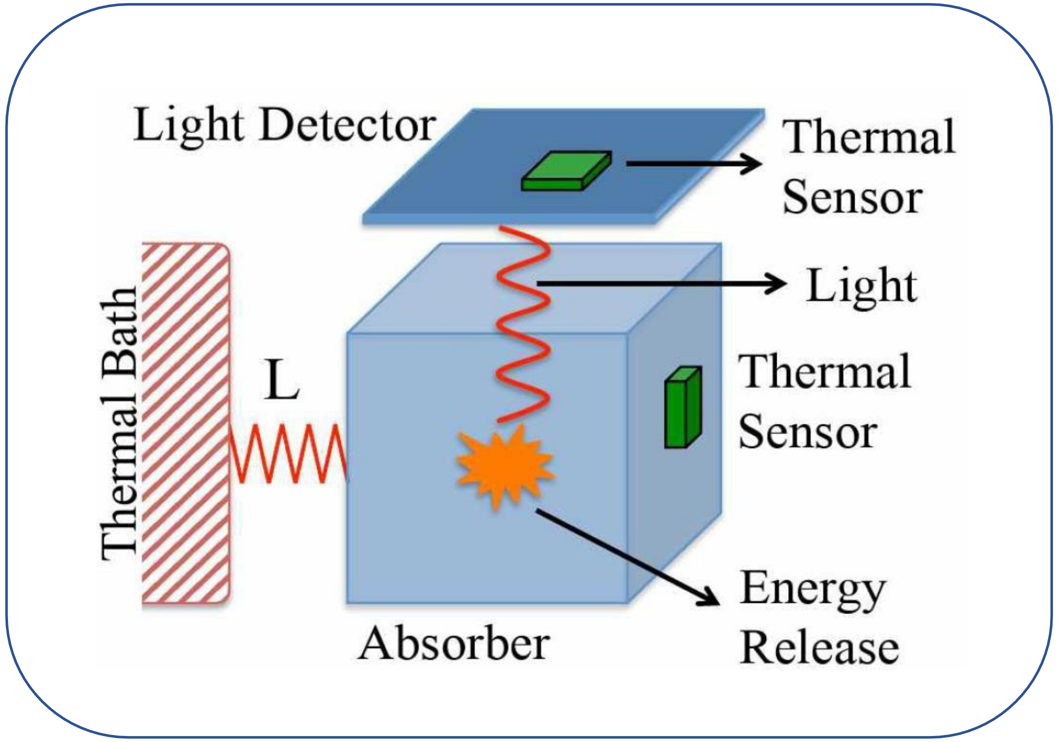
γ background

CUPID rationale

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



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

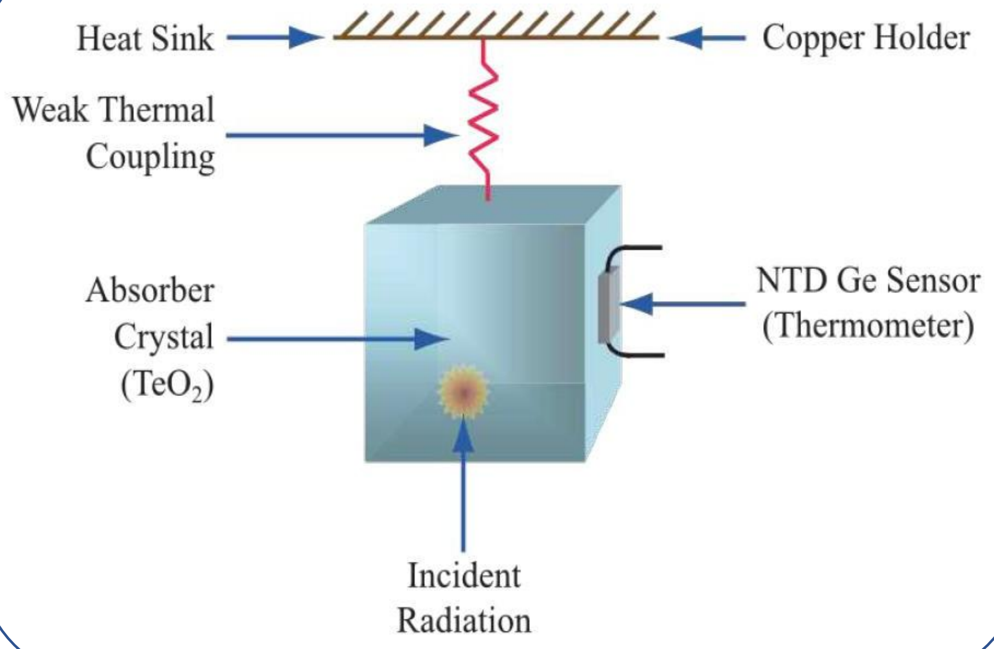


No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

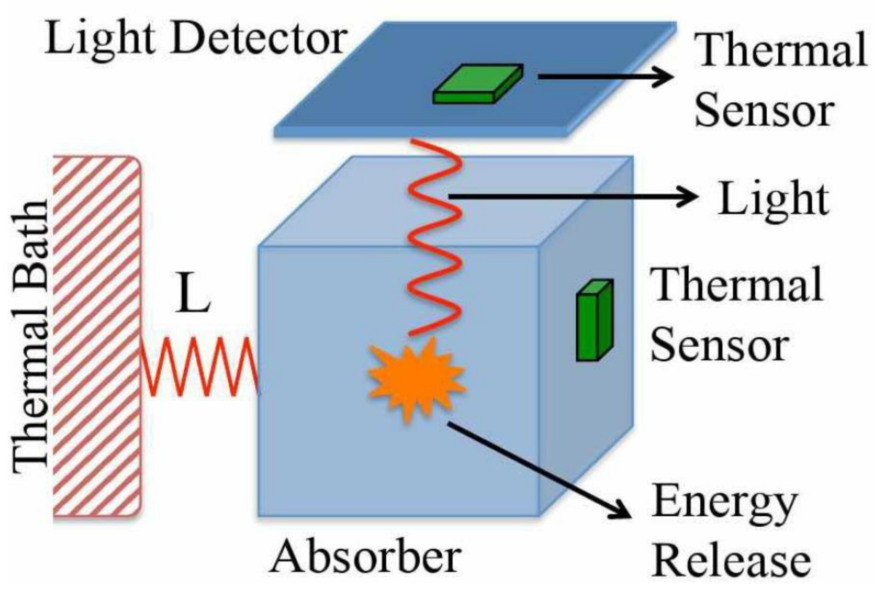
~~α background~~ ← **PID**
γ background

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**

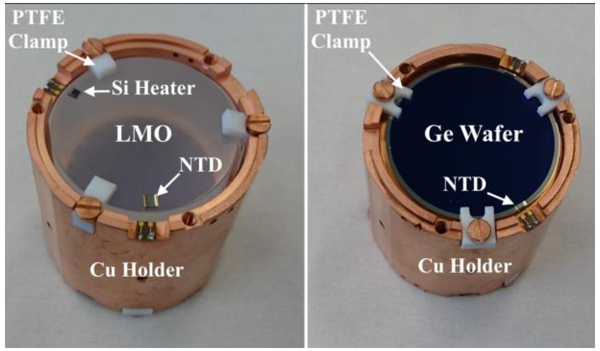
~~α background~~
~~γ background~~

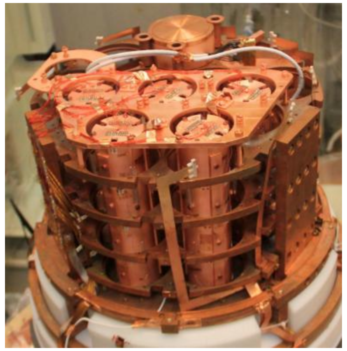
PID
$Q_{2\beta}$ = 3034 keV **> 2615 keV**

CUPID-Mo

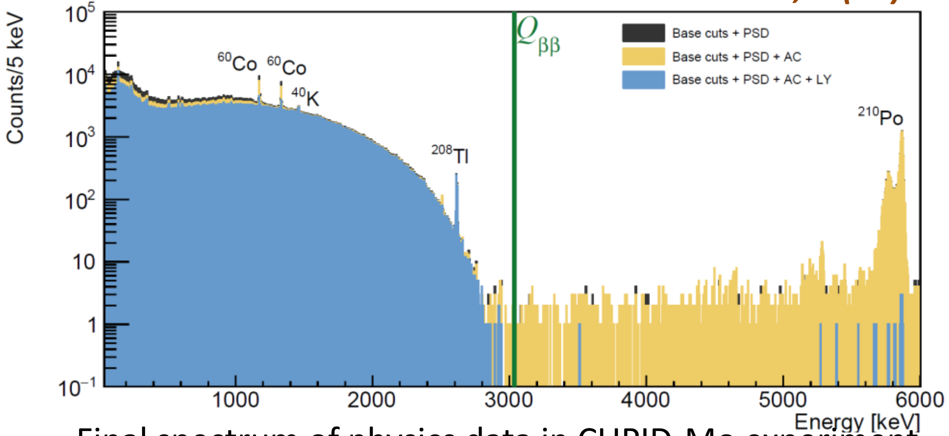
CUPID-Mo experiment

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



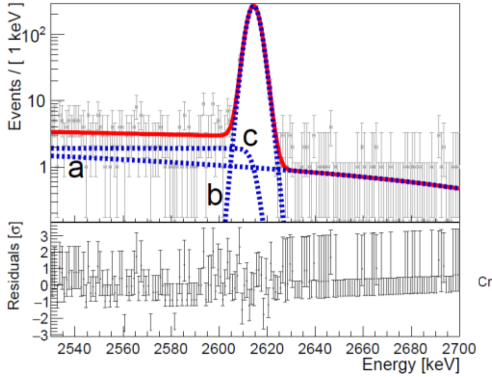


EPJ C. 2022 Nov 15;82(11):1033



Final spectrum of physics data in CUPID-Mo experiment

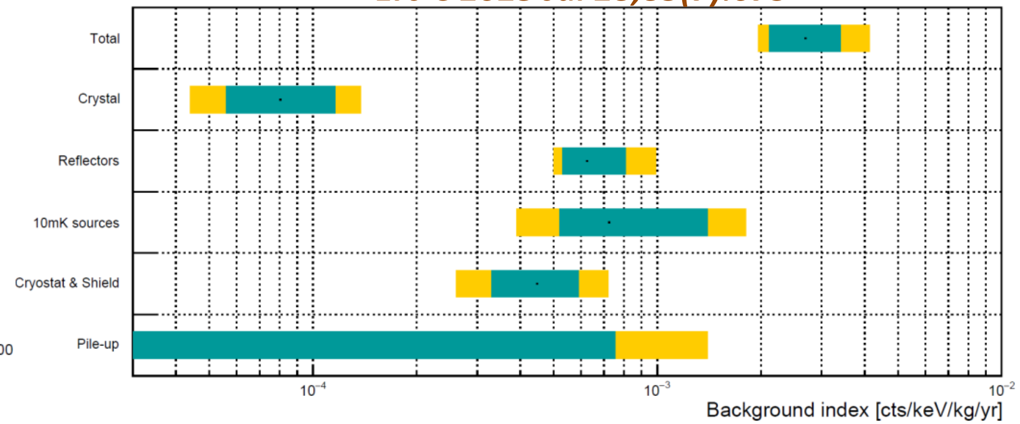
99.9% α particles rejection efficiency



Fit of Tl peak at 2615 keV

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

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



Contribution of the different sources to the BI

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

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

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

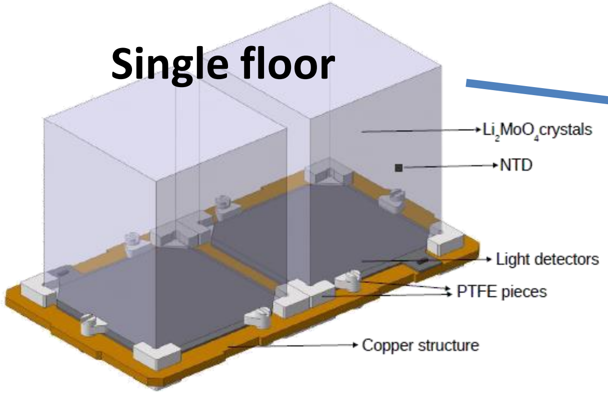
CUPID structure

CUPID pre-CDR *Eur. Phys. J. C 85, 737 (2025)*

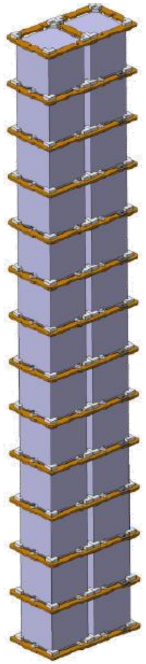
- Single crystal module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms

Baseline design
Gravity stacked structure

Single floor



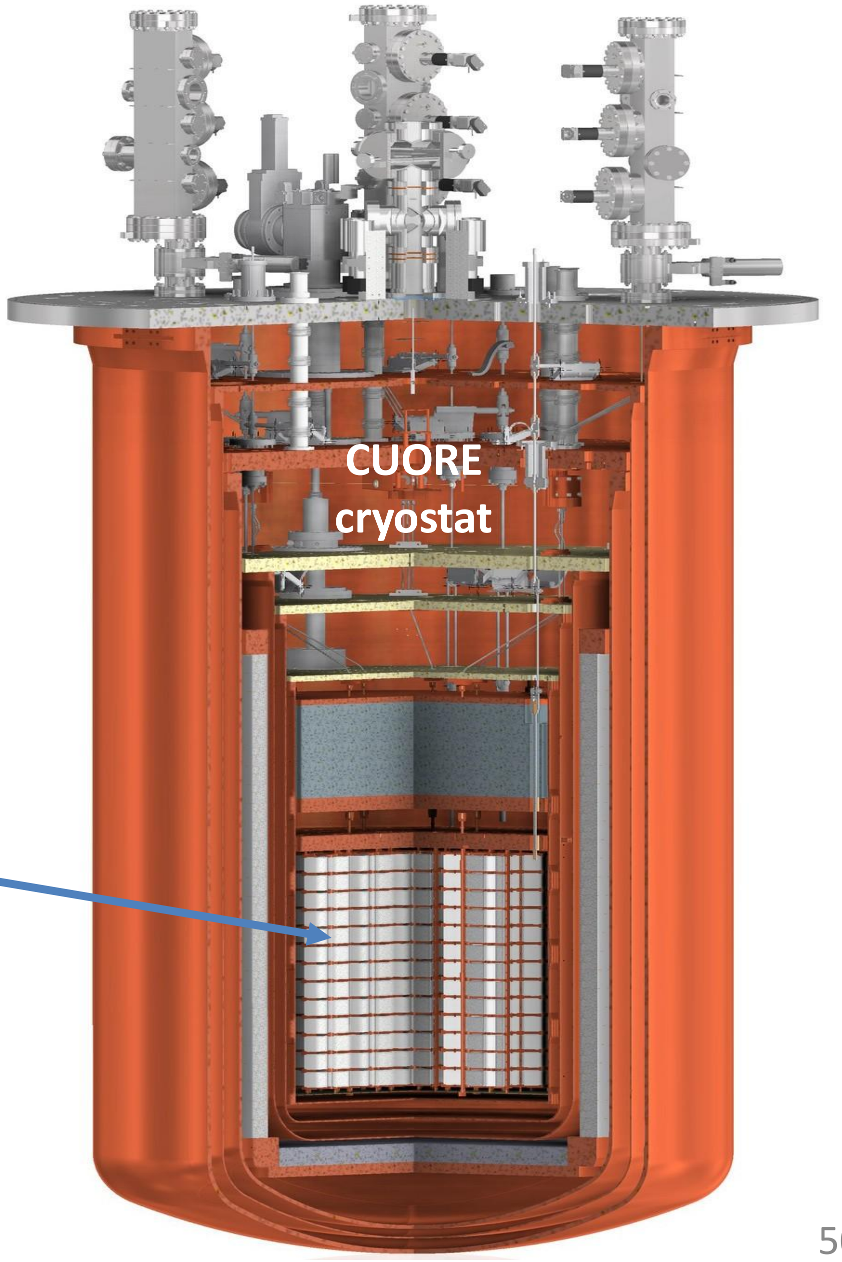
Single tower



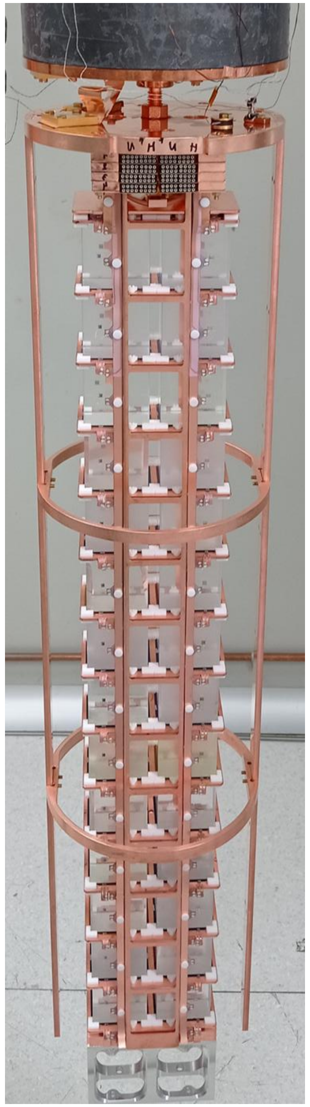
1710 Ge light detectors with SiO antireflective coating (each crystal has top and bottom LD)

- 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)

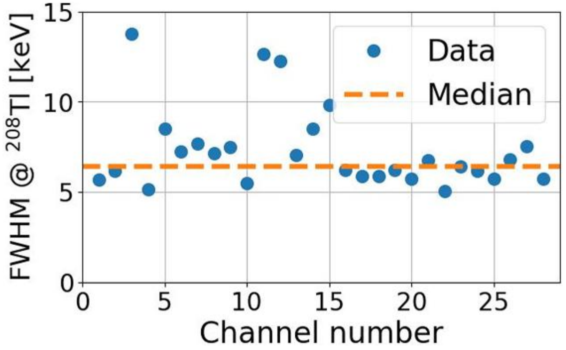
- 28 LMOs
- 30 Ge light detectors **without NTL effect**
- Tested at LNGS

Results:

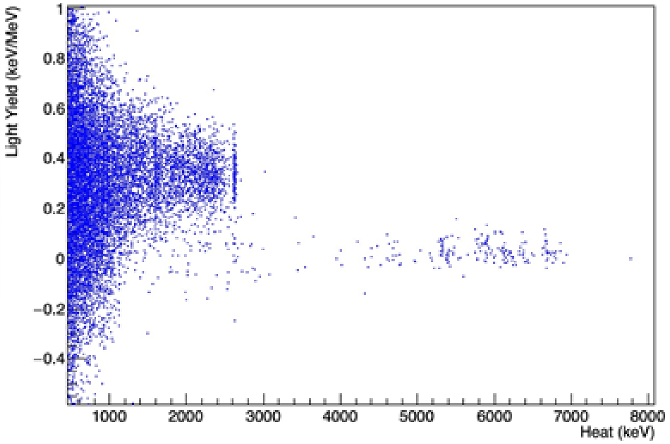
- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance:
  median $FWHM_{2615\ keV}$ = 6.2 keV
- median light yield: 0.34 keV/MeV
- α vs β,γ discrimination capability:

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

- 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)

- Preparation for the new test are currently ongoing

What's new?

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

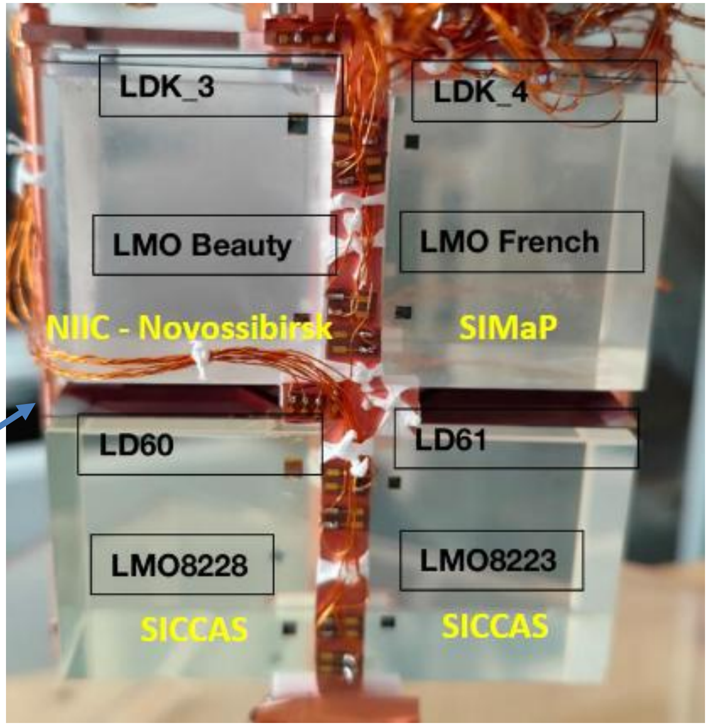
Status of crystal procurement

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 two enriched crystals were succesfully tested in cryogenic facility in LNGS and in Orsay



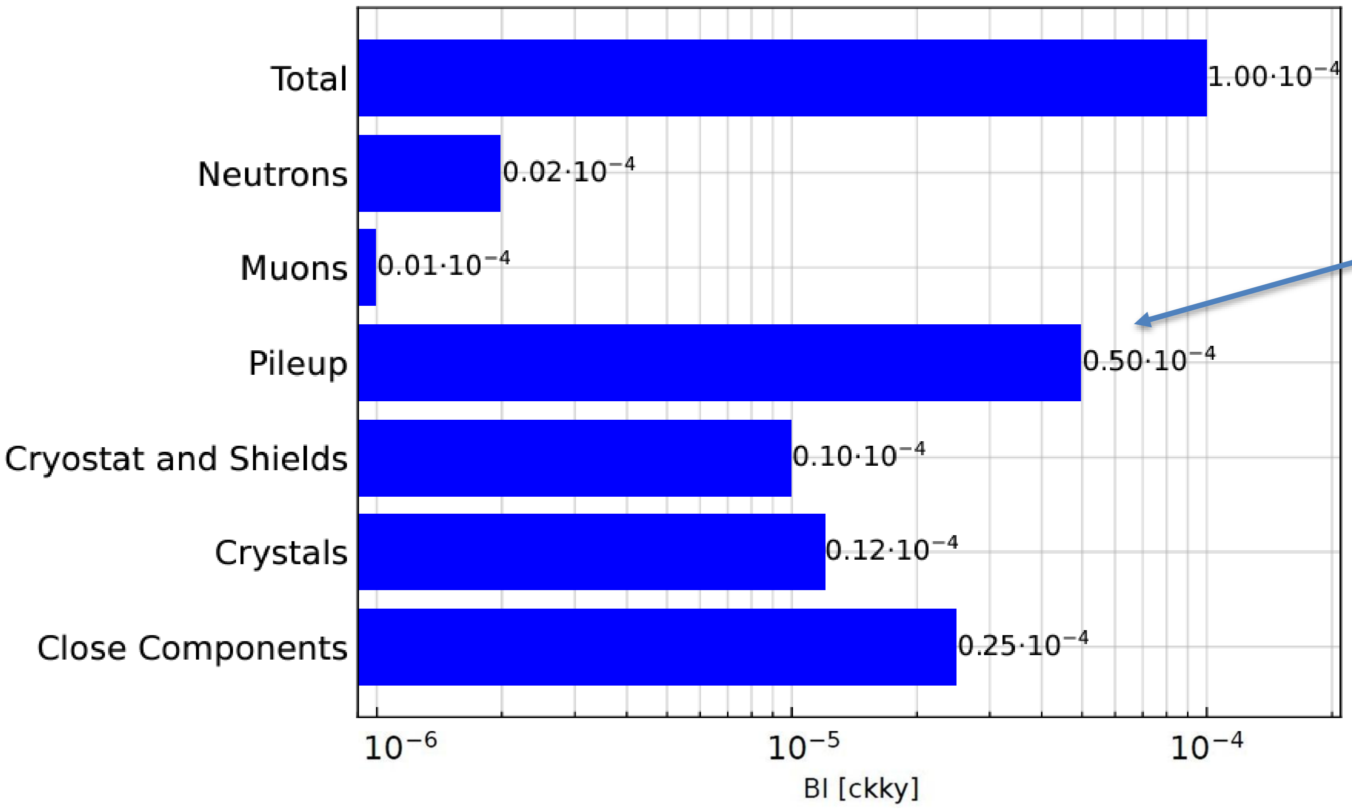
Investigating opportunities for production in France:

- We received a first natural Li_2MoO_4 crystal from Matias Velázquez (Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMaP, France) and performed the first tests in Orsay cryogenic facility
- The first Li_2MoO_4 crystals from Luxium Solutions were grown, we will receive them within the end of 2024

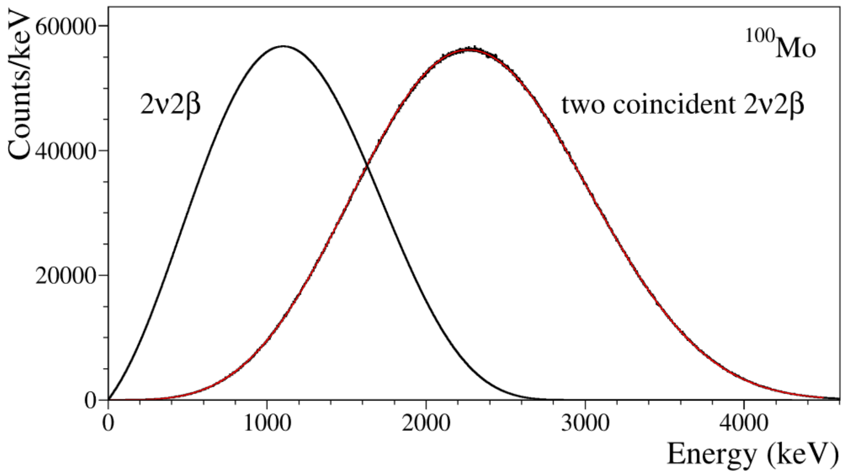
CUPID background budget

Two orders of magnitude better than in CUORE

CUPID background goal:
BI = 10^{-4} counts/keV/kg/year



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



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
- ~ 1 ms ← Light channel

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

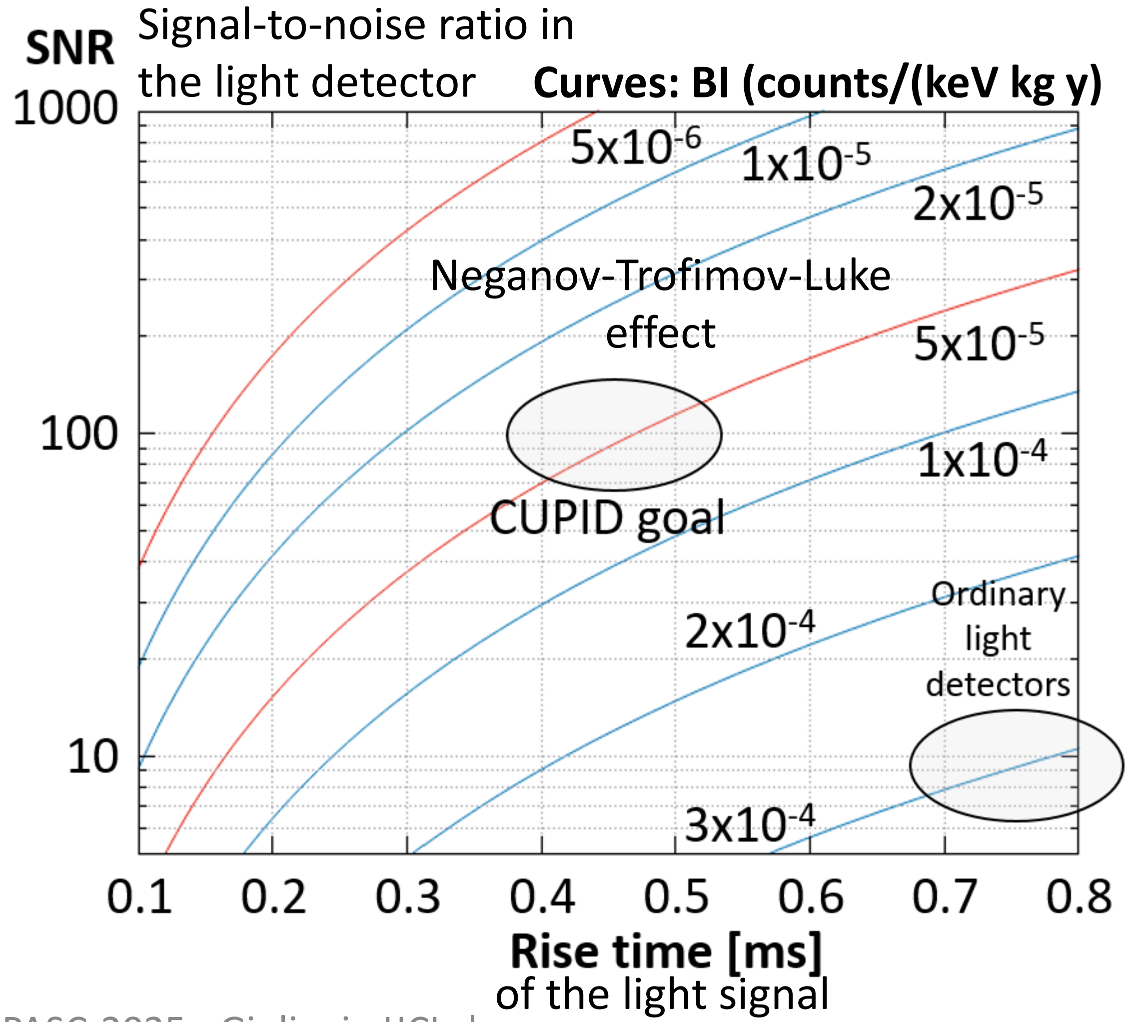
Phys. Rev. D 110 (2024) 052003

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

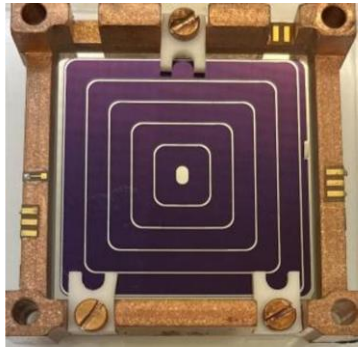
Pile-up and light detector role

- **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)**

NIMA 940, 320 (2019)



- 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**

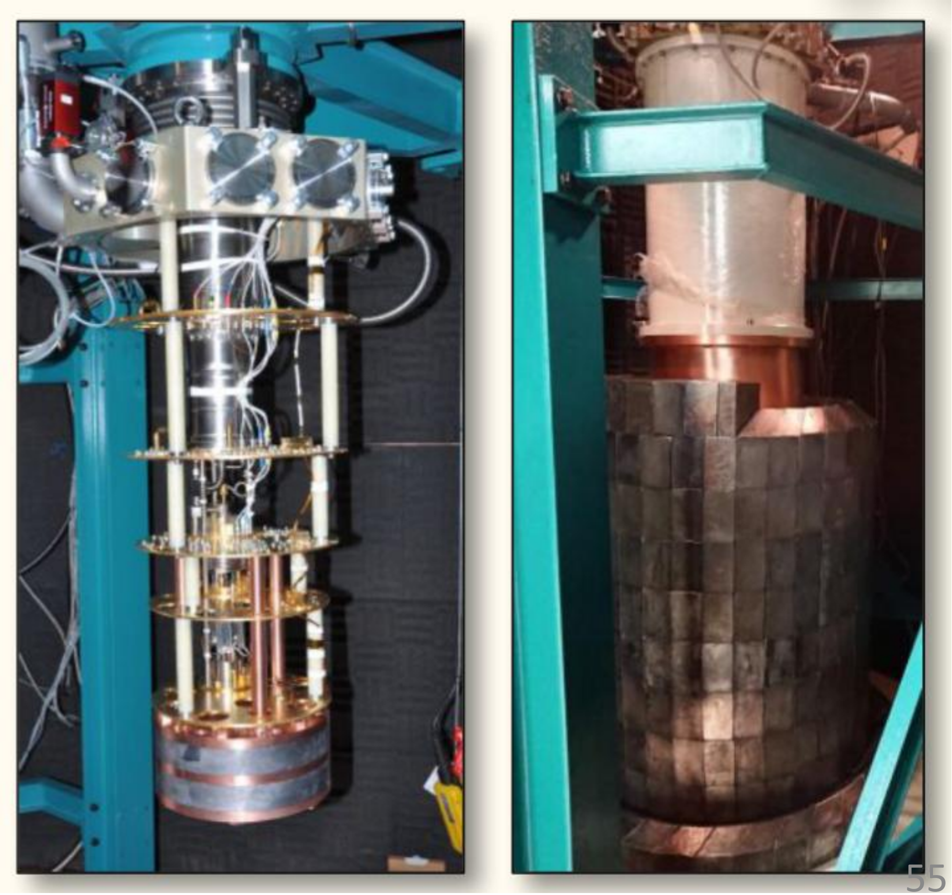




CROSS project

A standalone experiment and a laboratory for CUPID

The CROSS experiment aims to detect $0\nu2\beta$ developing 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

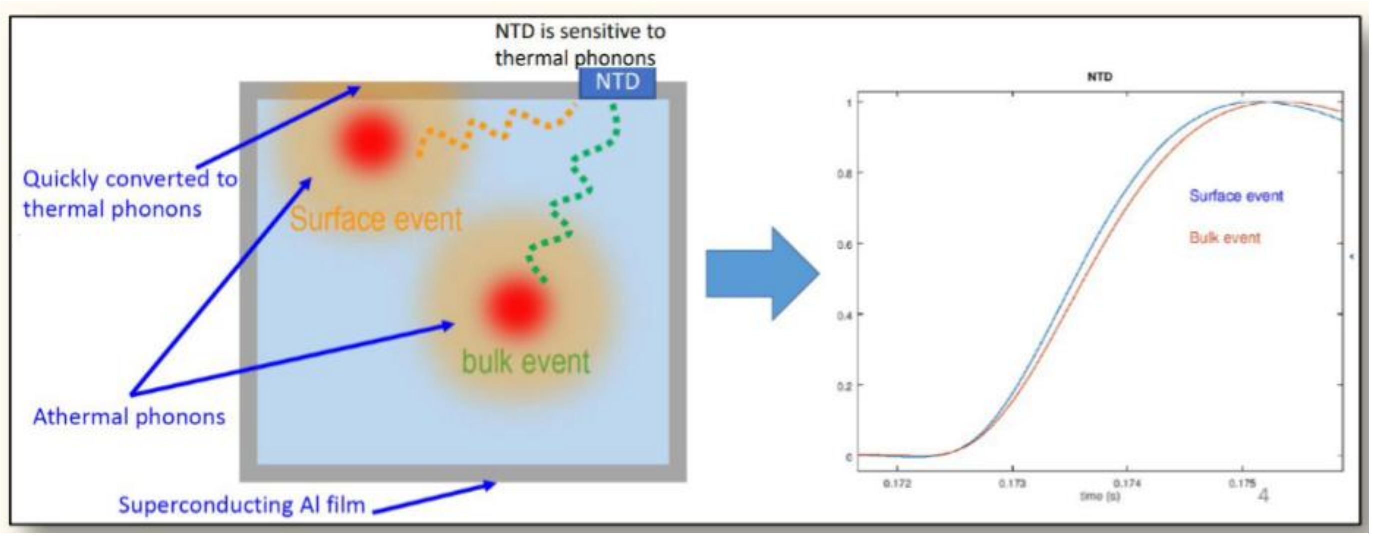
New technologies:

- Surface coating of bolometers to discriminate between bulk and α/β surface events
- Neganov-Trofimov-Luke (NTL) Light Detectors development and optimization to be used with scintillating bolometers

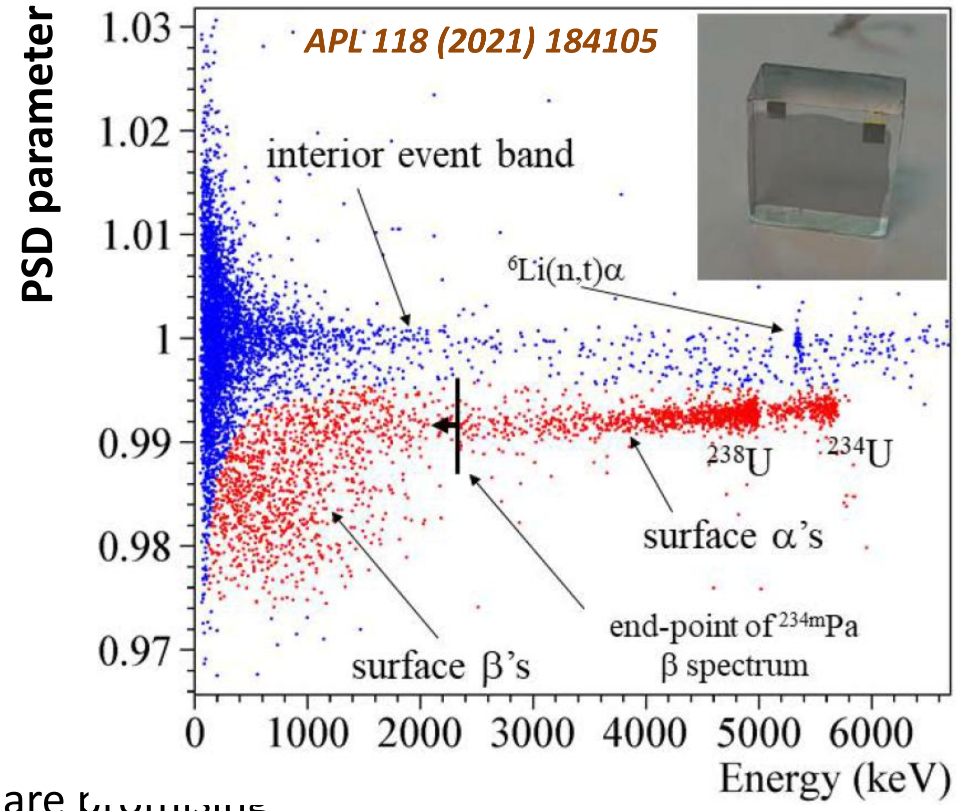
CROSS project: discrimination of surface events

- 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)



Mixed α/β source



Proof of concept achieved with small prototypes

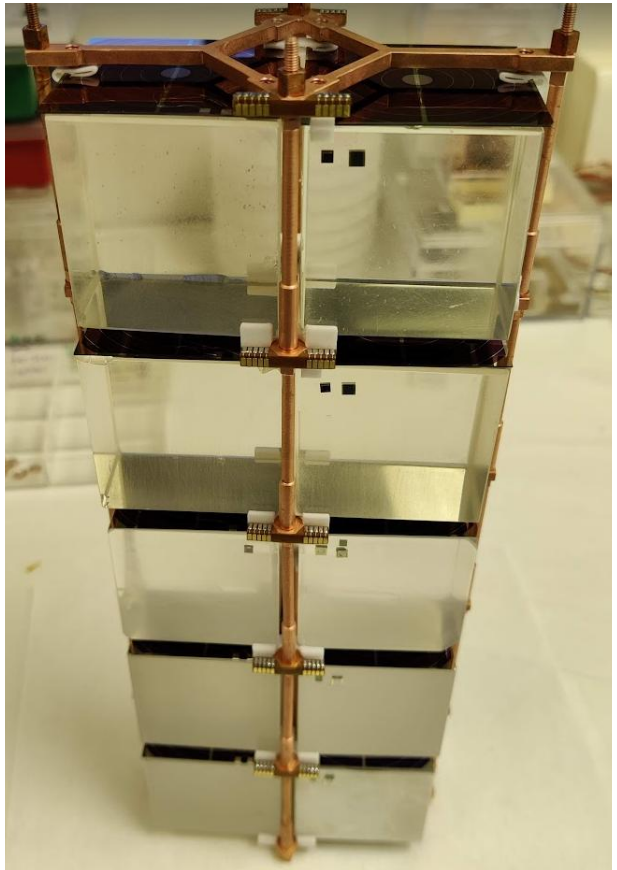
Both **surface α's and β's** are separated from bulk events

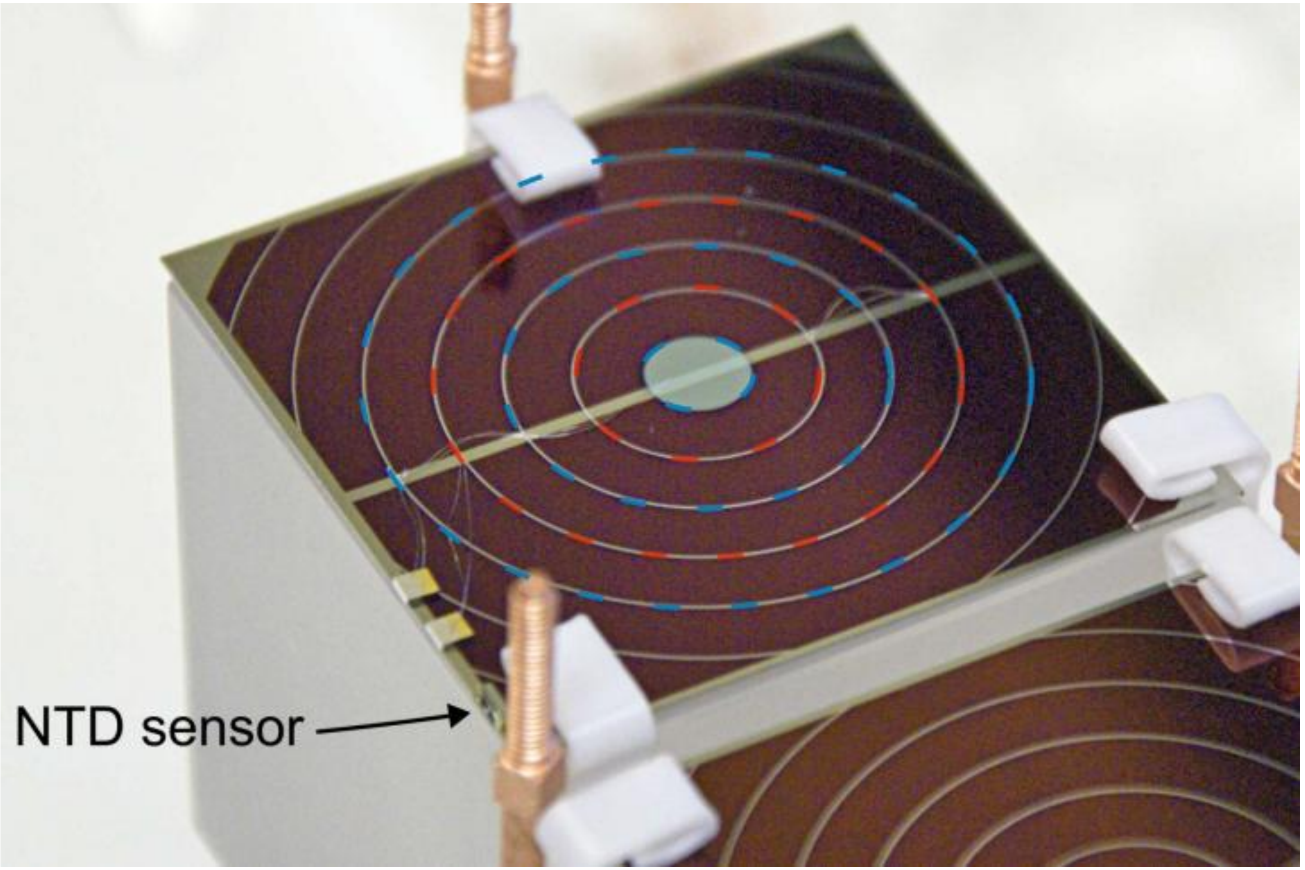
Tests with small (2 × 2 × 1 cm^3) Li_2MoO_4 crystals coated with Al-Pd are promising

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

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



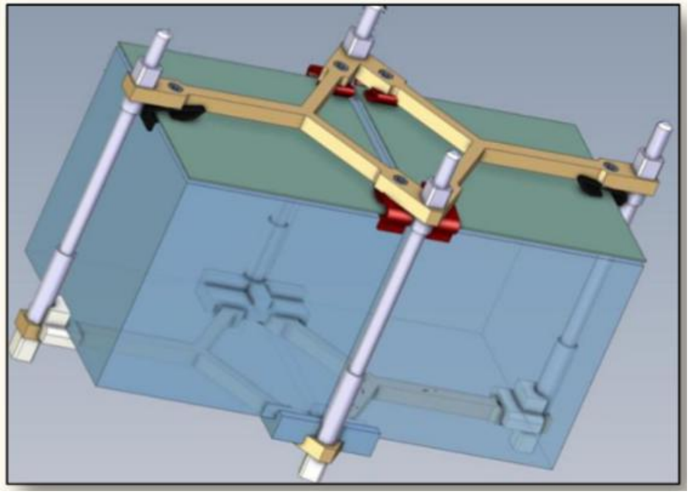


CROSS demonstrator

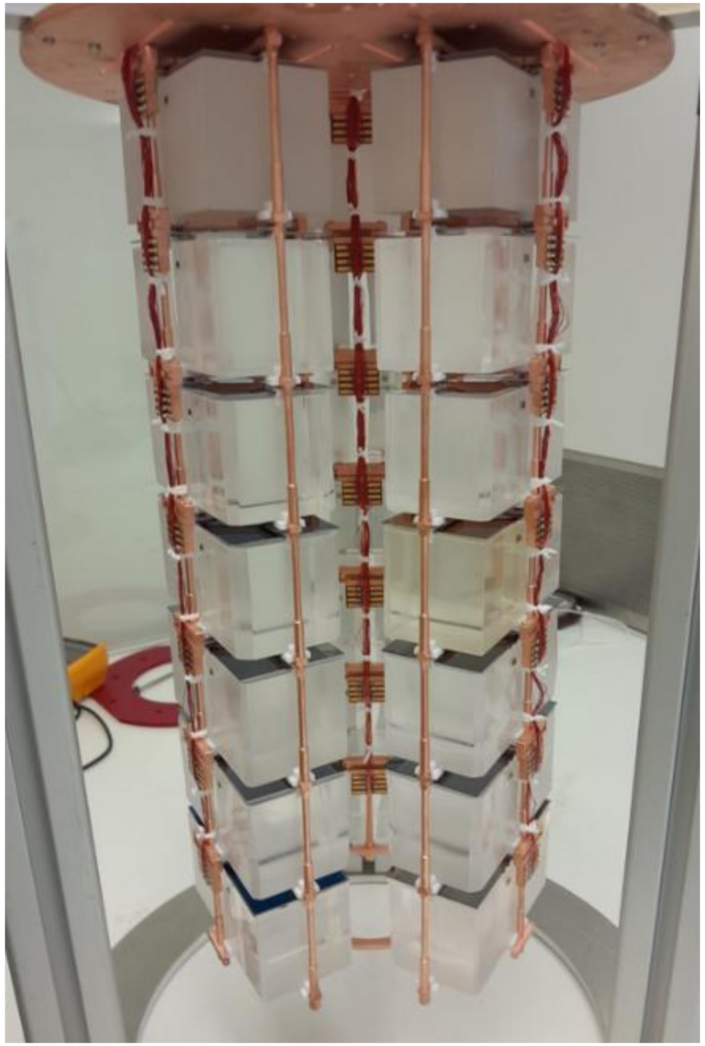
3 towers with 7 floors each
Test of different light detectors in each tower:
- Ge wafers with circular electrodes
- Ge wafers with square electrodes
- Si wafers with spiral electrodes

In total: 36x $Li_2{}^{100}MoO2$ and 6x $^{130}TeO_2$
- **Total mass of ^{100}Mo: 4.7 kg**
- **Total mass of ^{130}Te: 2.6 kg**

Detector assembly already started
Installation and commissioning in early 2025 – data taking for 2 years



2024 *JINST* 19 P09014



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 $\mathbf{T_{1/2}^{0\nu} > 2.9 \cdot 10^{24}\ yr}$

D. Cintas, NuDM-2024

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

Coming back to CUPID: staged development

NEW

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

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Previous baseline		$Li_2{}^{100}MoO_4$ contract	$Li_2{}^{100}MoO_4$ production 355 xtls/year					construction and commissioning		data	
Stage I 1/3 of the crystals		$Li_2{}^{100}MoO_4$ contract	$Li_2{}^{100}MoO_4$ production 210 xtls/year				data				
Full CUPID Add 2/3 of the crystals						$Li_2{}^{100}MoO_4$ production 270 xtls/year					data

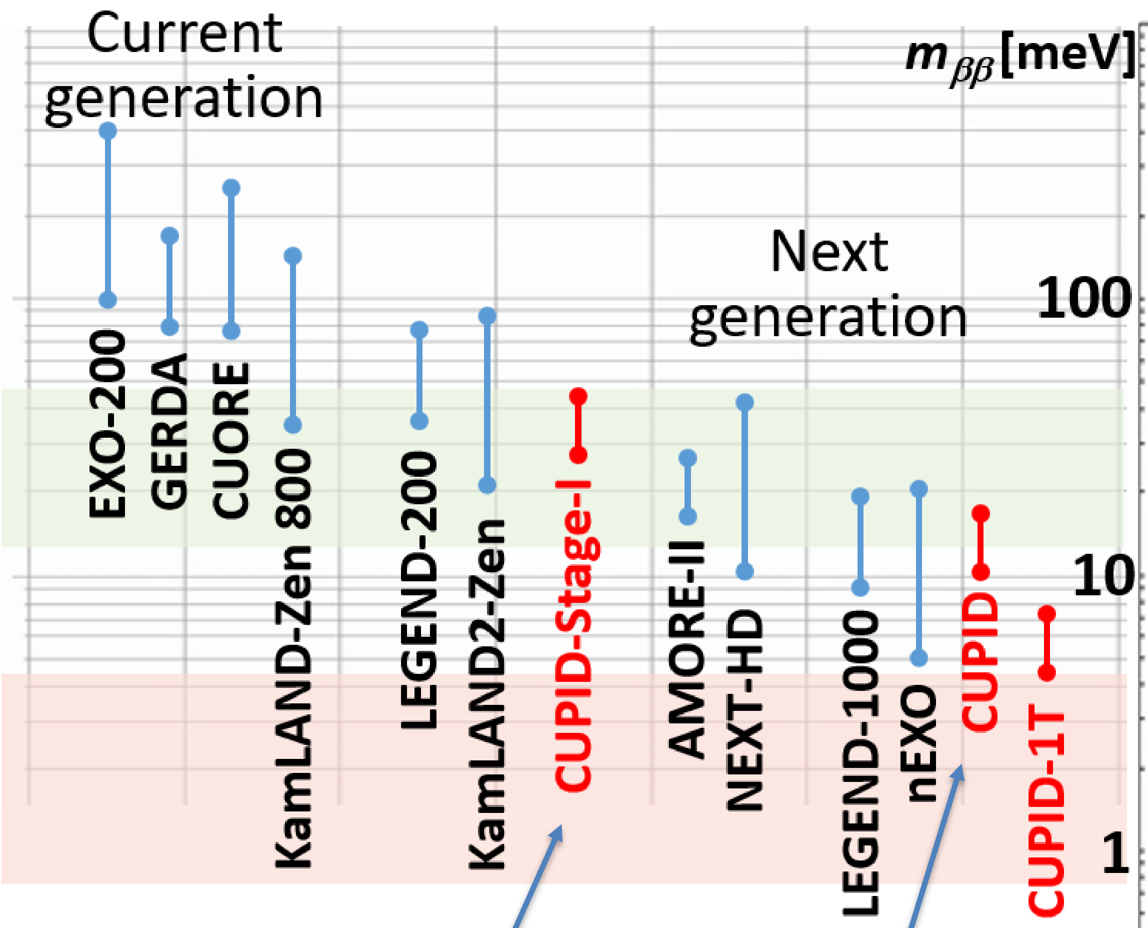
CUORE cryostat upgrade

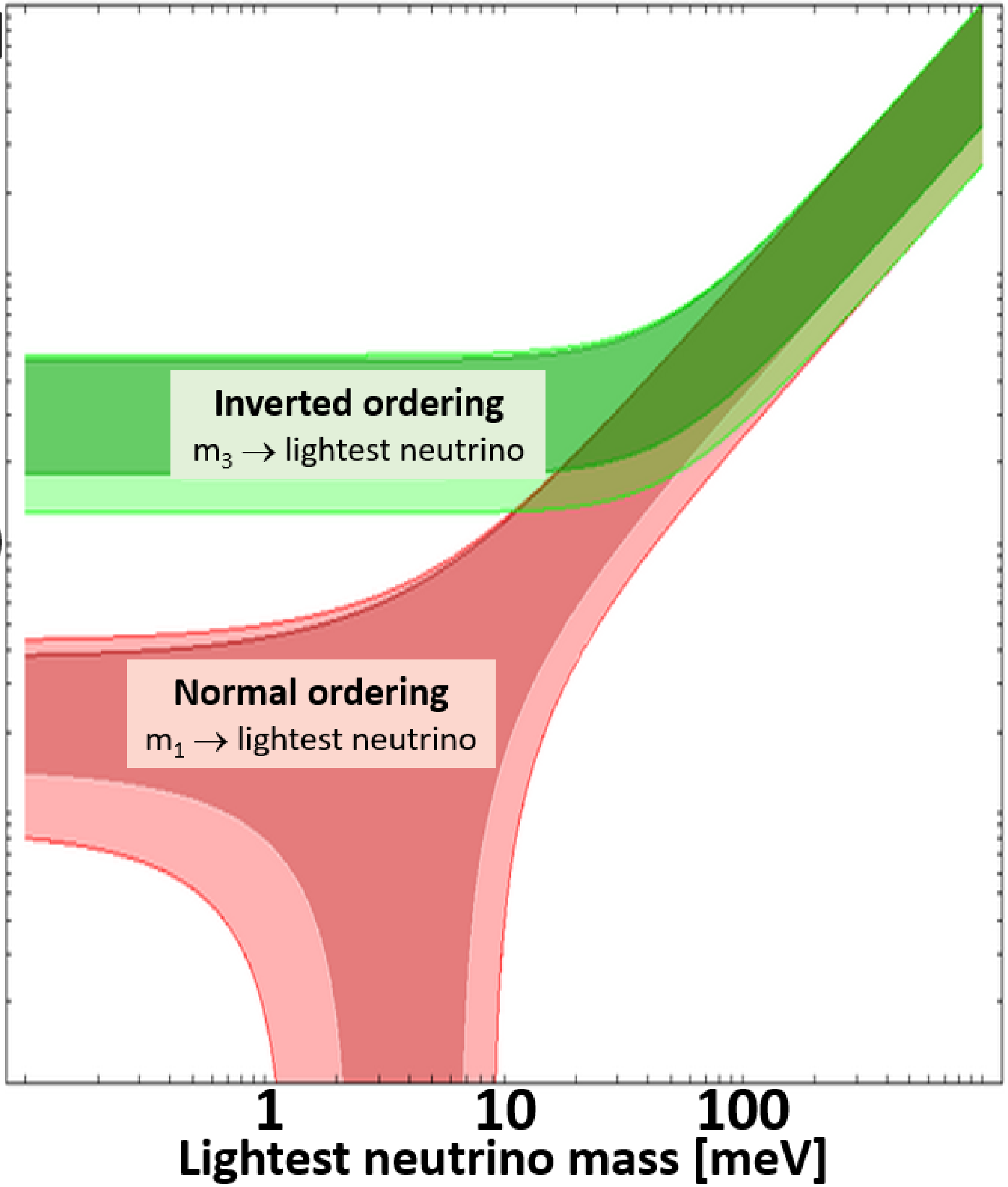
$\sim 2\times10^{26}$ y

$\sim 4\times10^{26}$ y

CUORE cryostat upgrade

CUPID: sensitivity





Exclusion sensitivities

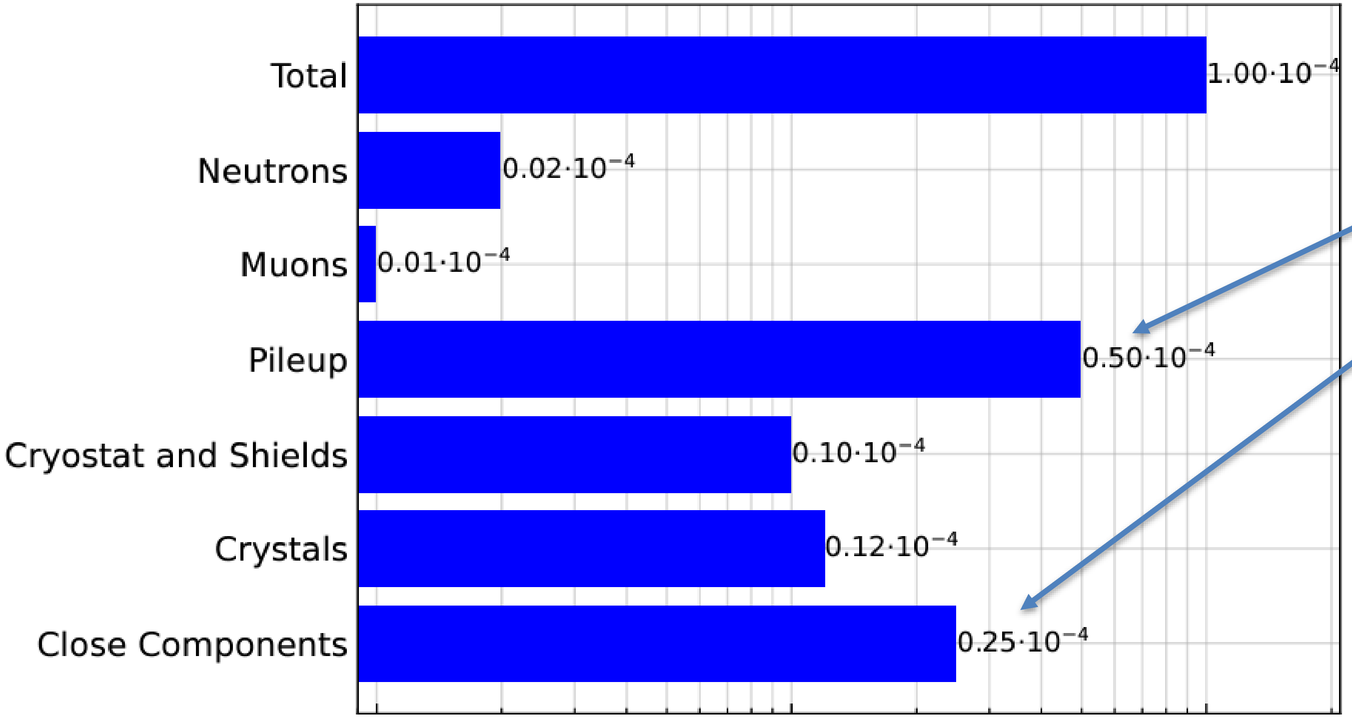
$T^{0\nu}_{1/2} > 2.0 \cdot 10^{26}$ y and $m_{\beta\beta} < 27 - 45$ meV

3 y live time $T^{0\nu}_{1/2} > 1.4 \cdot 10^{27}$ y and $m_{\beta\beta} < 10 - 17$ 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 expected counts in FWHM)



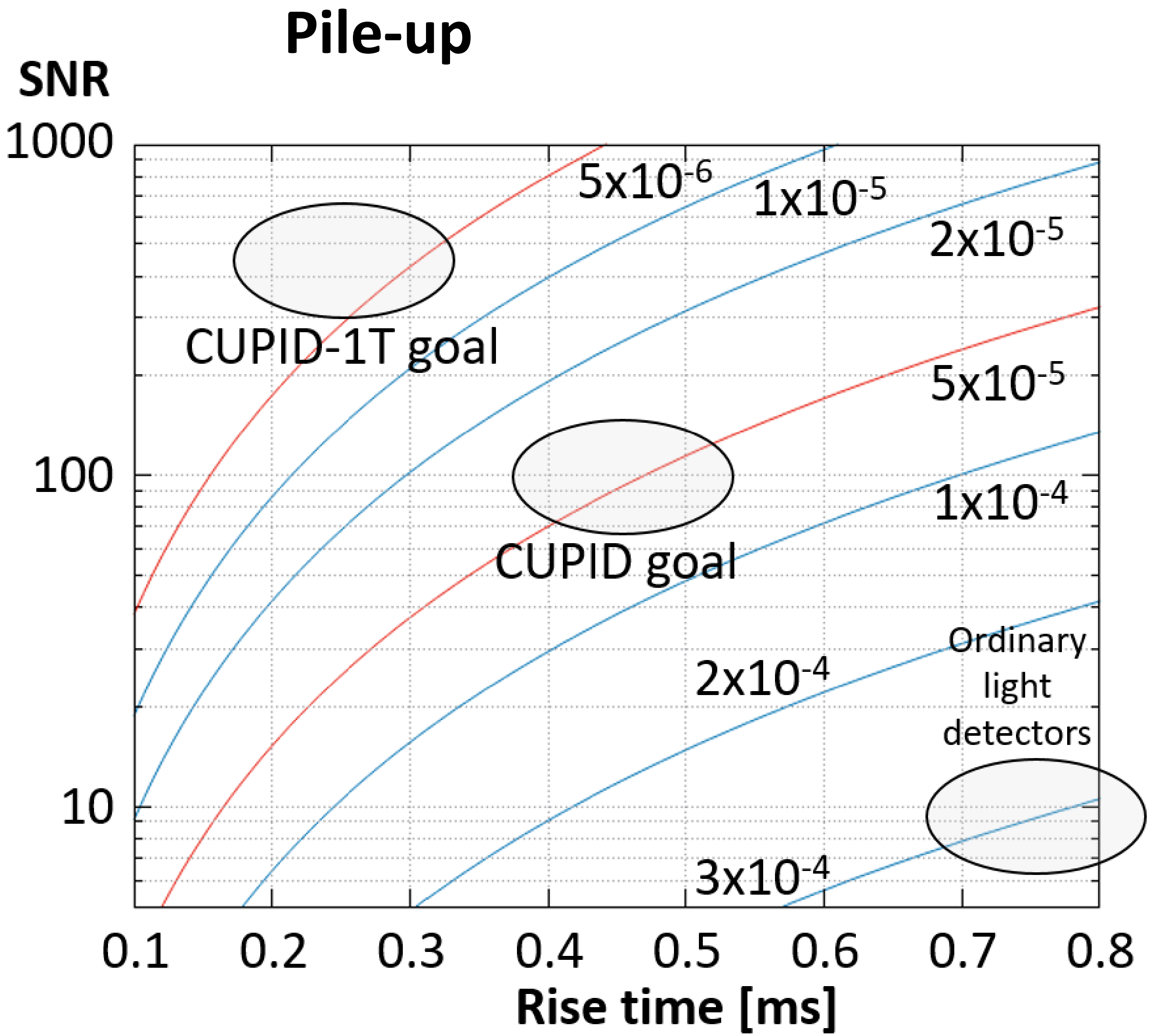
These two components must be reduced by one order of magnitude

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?



Light detector performance

With respect to CUPID

- Increase SNR x5
- Reduce Rise-time x2

Two approaches under exploration

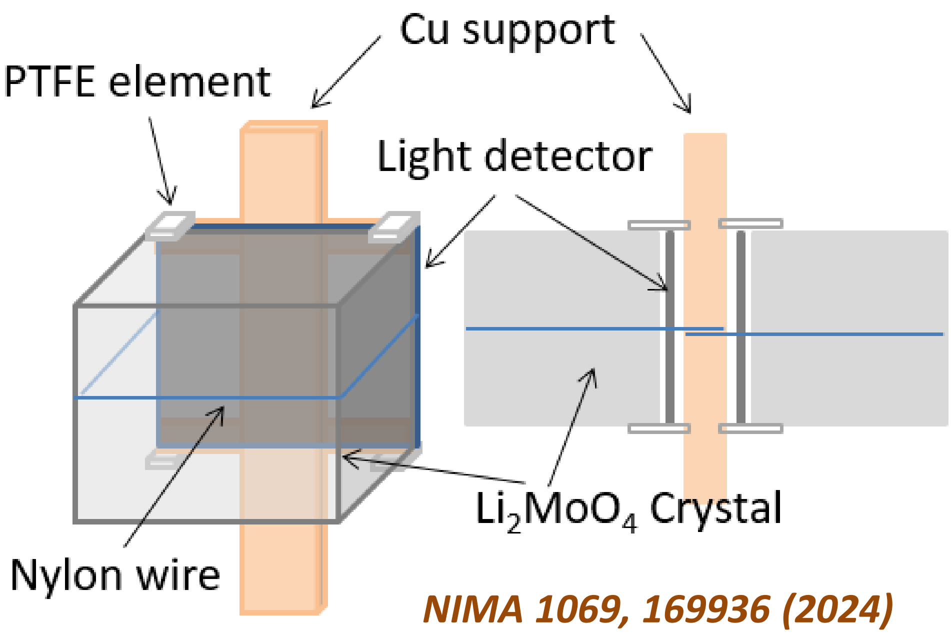
- Increase Li_2MoO_4 light emission by doping
- Change phonon sensor in light detector, moving to high impedance NbSi TES

Is CUPID-1T feasible?

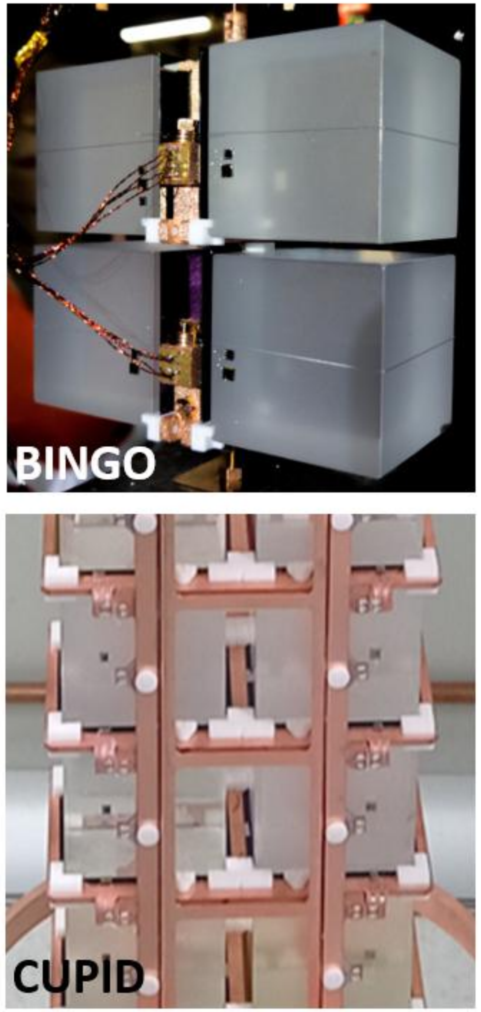
Close components

BINGO approach – use light detector to shield copper support

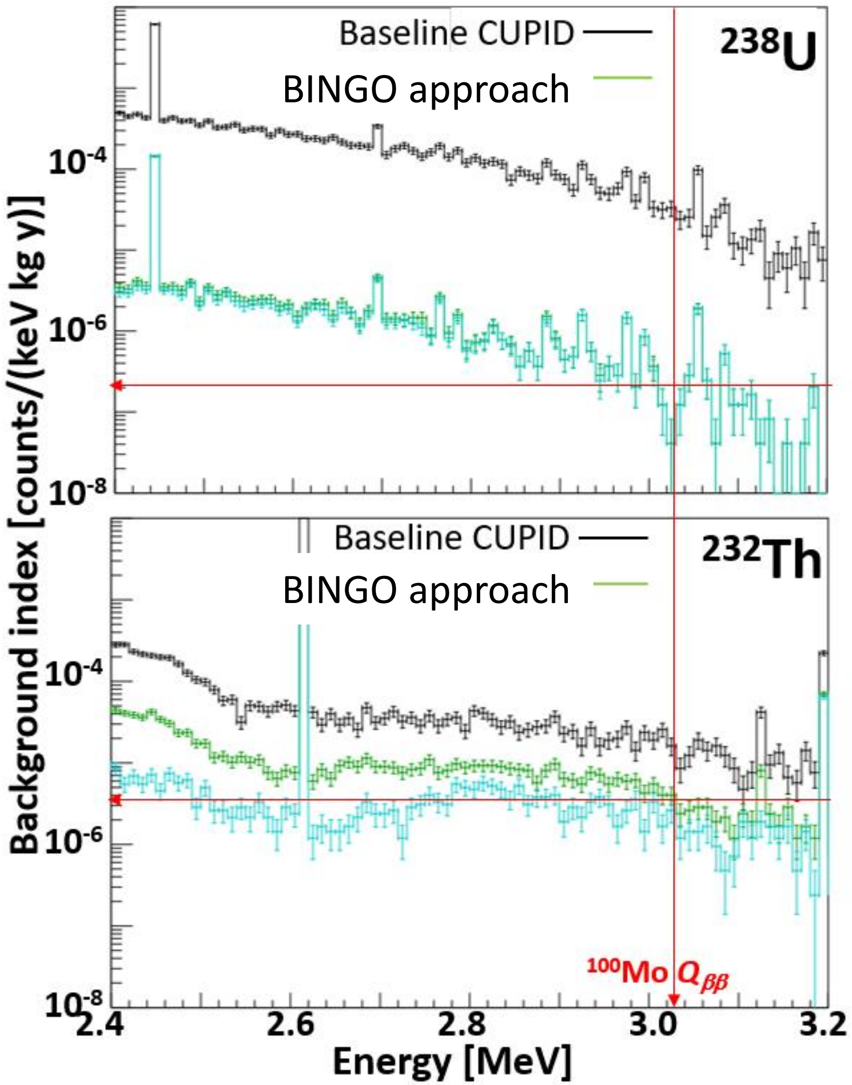
- Dramatic reduction of the passive material facing the crystals
- Abate background by anti-coincidence



NIMA 1069, 169936 (2024)



Simulation CUPID vs. BINGO



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 ($CdWO_4$)

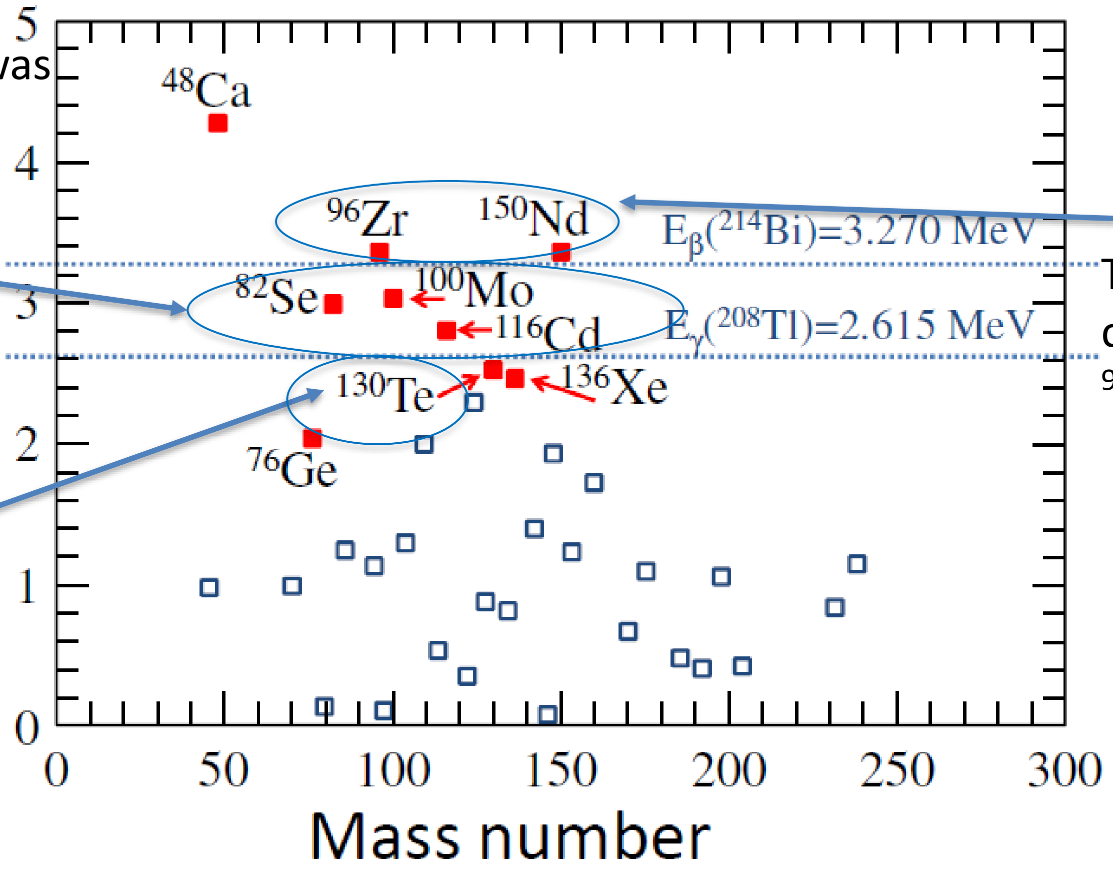
Phys. Rev. Lett. 129, 111801

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

Conclusions

- $0\nu2\beta$ is a crucial process, not only for neutrino physics
- Next-generation experiments have a good discovery potential
- Many projects aim at extending the present sensitivity
- The bolometric technique is a promising approach for current and future searches
- Despite all that, that elusive peak still escapes detection…

BACK-UP

m_{ee} distribution in the parameter space

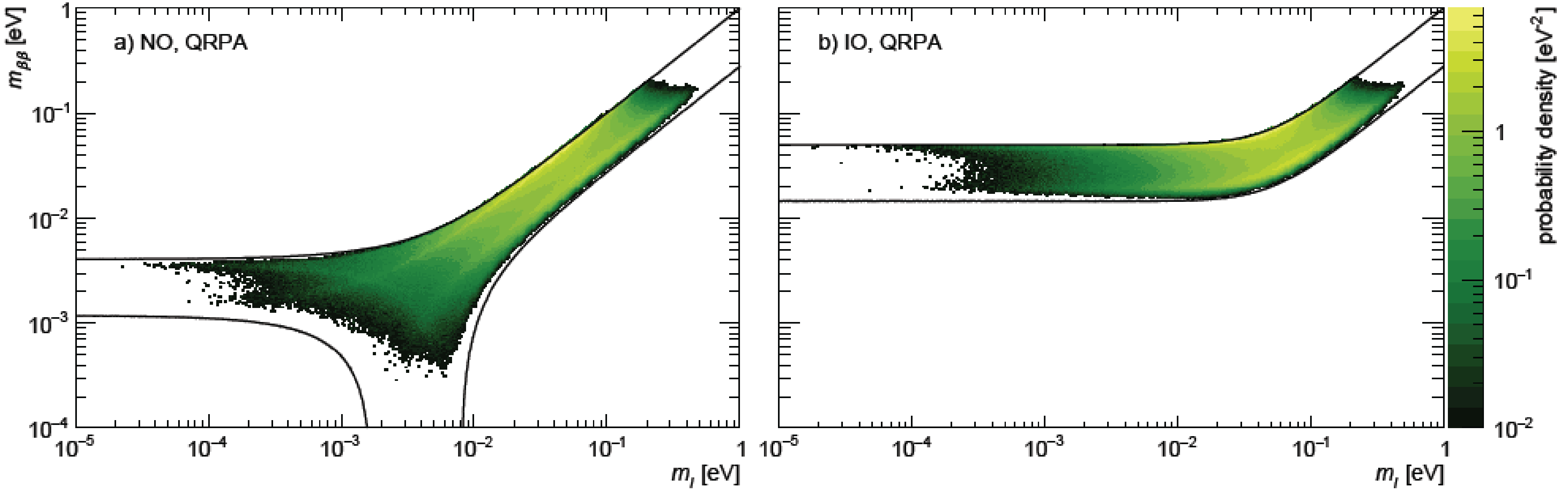
Phys. Rev. D 96, 053001 (2017)

Global Bayesan analysis including neutrino oscillations, tritium, double beta decay, cosmology

Ignorance of the scale of the parameters $\rightarrow$ **Scale-invariant prior distributions**

- $\Sigma = m_1+m_2+m_3$, Δm_{ij}^2: **logarithmic**
- Angles and phases in PMNS matrix: **flat**

Marginalized posterior distributions of $m_{\beta\beta}$



Approaches and experiments

source = detector

			NOW	MID-TERM	LONG-TERM
Scalability	**Fluid embedded source**	Xe-based TPC	EXO-200 NEXT-WHITE	NEXT-100 PandaX-III	nEXO NEXT-1t NEXT-BOLD PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	**Crystal embedded source**	Germanium diodes	GERDA-II MAJORANA DEM.	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II CUPID	CUPID-reach CUPID-1T

Approaches and experiments

source = detector		NOW	MID-TERM	LONG-TERM
Fluid embedded source	Xe-based TPC	EXO-200 NEXT-WHITE	NEXT-100 PandaX-III	nEXO NEXT-1t NEXT-BOLD PandaX-III 1t
	Liquid	KamLAND-Zen 800		KamLAND2-Zen SNO+ phase II
embedded source				LEGEND 1000
	Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II CUPID	CUPID-reach CUPID-1T

alability

High ΔE

These experiments aim to explore deeply or fully the IO region and to cover a substantial part of the NO region

$T_{1/2} > 10^{27} – 10^{28}$ y – $m_{ee} <$ ~20 meV

Approaches and experiments

source = detector | **NOW** | **MID-TERM** | **LONG-TERM**

Scalability

EXO-200

nEXO

- Isotope mass is $0\nu2\beta$ source but also a background indicator $\rightarrow$ fiducialization
- Low energy resolution – 25 keV FWHM (NEXT) – 270 keV FWHM (KamLAND-Zen)
- Space resolution: tracking or impact point (single-site vs. multi-site) depending on the project
- The limit (signal) comes from a global reconstruction of the background over a wide energy range
- If isotope is strongly (~1 % level) diluted (SNO+, KamLAND-ZEN), finally limited by solar neutrinos if no directionality

SNO+ phase I

SNO+ phase II

High ΔE and ε

Germanium

GERDA-II

LEGEND 200

LEGEND 1000

- High geometrical efficiency (> 70%)
- High energy resolution –3 keV FWHM in Ge diodes – 5 keV FWHM in bolometers
- Granularity, pulse shape discrimination, particle identification methods
- The limit (signal) comes from a narrow region around the Q value
- The background model is used mainly to understand and to improve

CUPID-0, CUPID-Mo

CUPID-1T

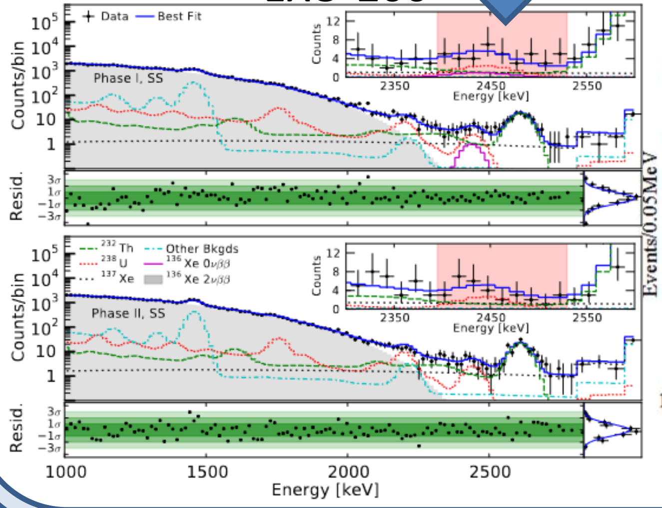
Approaches and experiments

source = detector

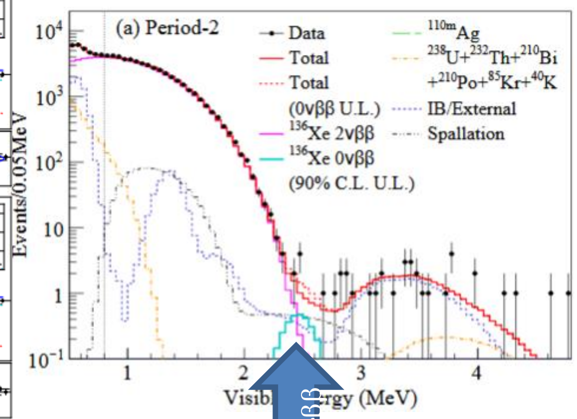
NOW | MID-TERM | LONG-TERM

$Q_{\beta\beta}$

EXO-200

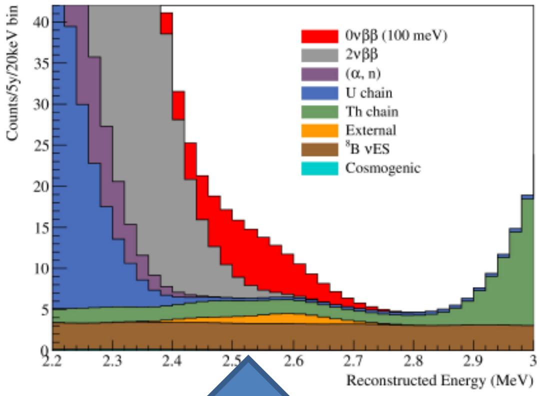


KamLAMD-Zen



$Q_{\beta\beta}$

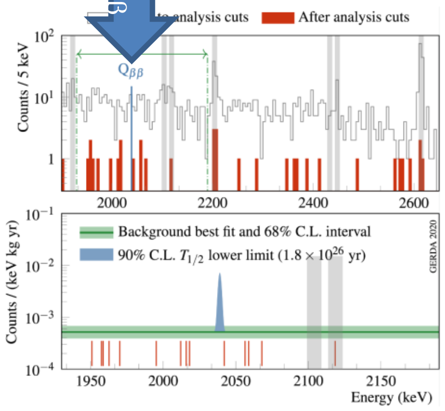
SNO+



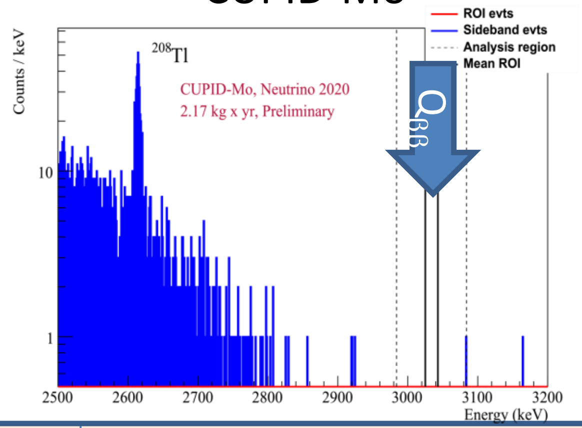
$Q_{\beta\beta}$

$Q_{\beta\beta}$

GERDA

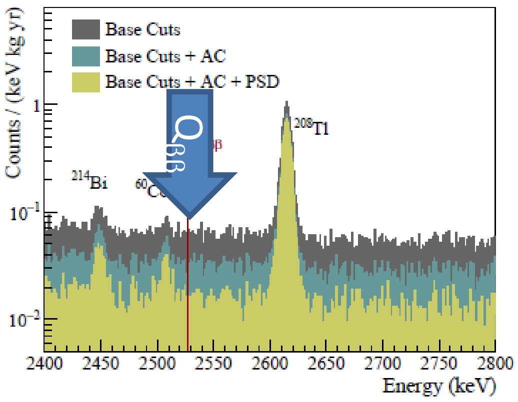


CUPID-Mo



$Q_{\beta\beta}$

CUORE



$Q_{\beta\beta}$

^{136}Xe

Phys. Rev. Lett. 123, 161802 (2019)

EXO-200

EXO-200 has recently completed data taking

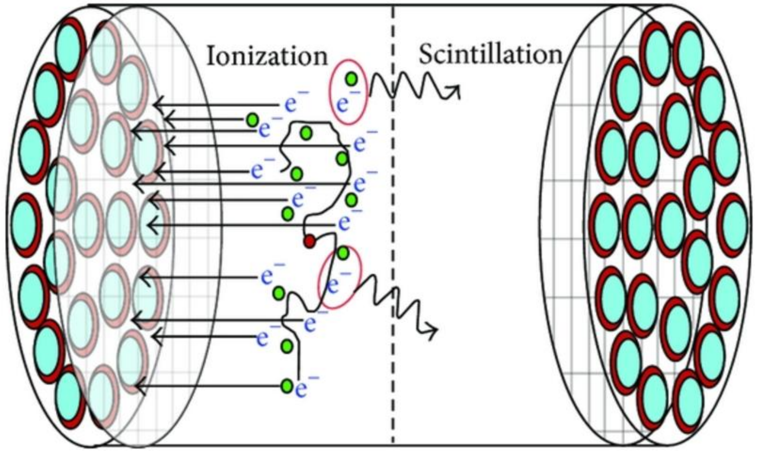
WIPP - US **Exposure: 234.1 kg×y**

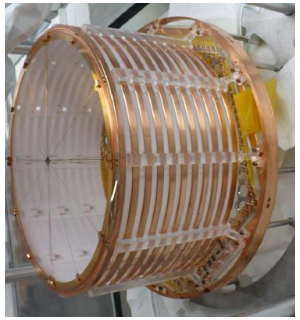
Final results: $T_{1/2} > 3.5\times10^{25}$ y

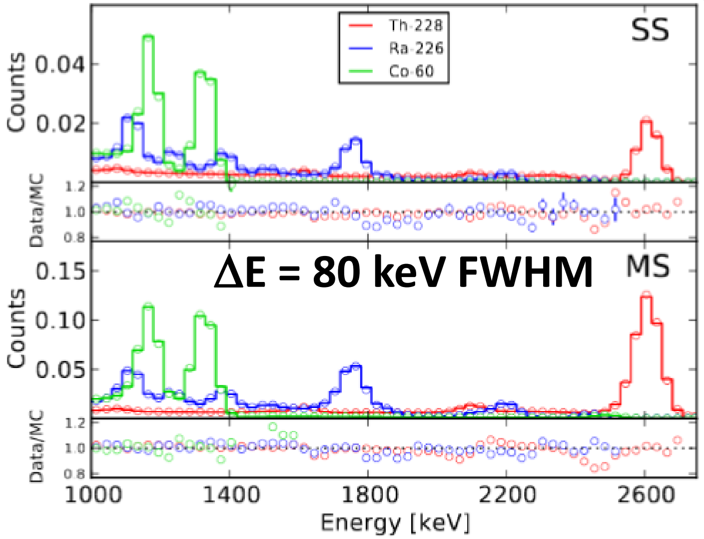
$m_{ee} < 93 – 286$ meV

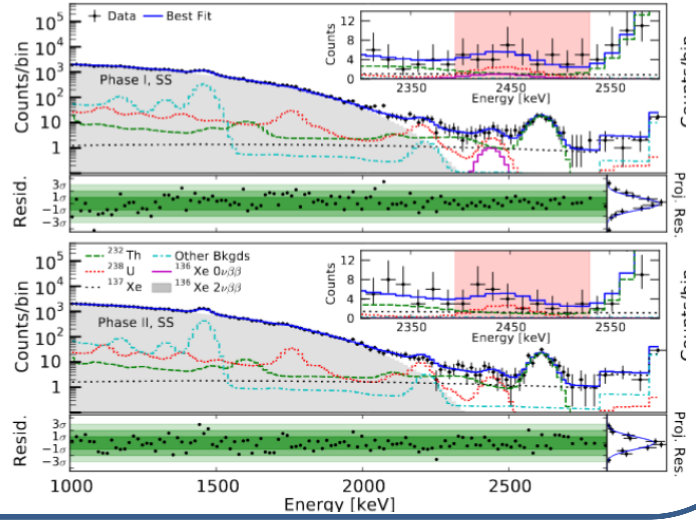
Enriched liquid xenon TPC →

Discrimination between **Multi-site (MS)** (background) vs **Single-site (SS)** (including signal) events









^{136}Xe *arXiv:2106.16243*

EXO-200 → nEXO

EXO-200 has recently completed data taking

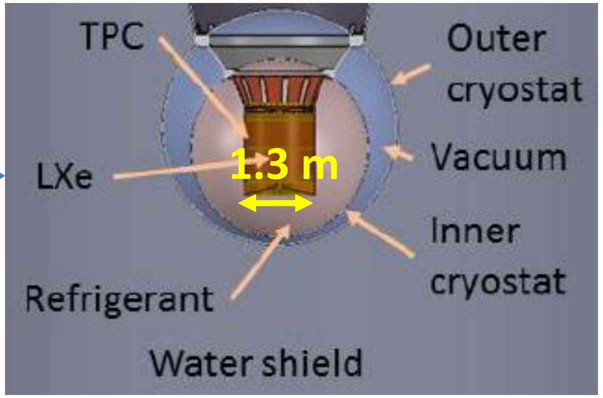
WIPP - US **Exposure: 234.1 kg×y**

Final results: $T_{1/2} > 3.5 \times 10^{25}$ y
$m_{ee} < 93 - 286$ meV

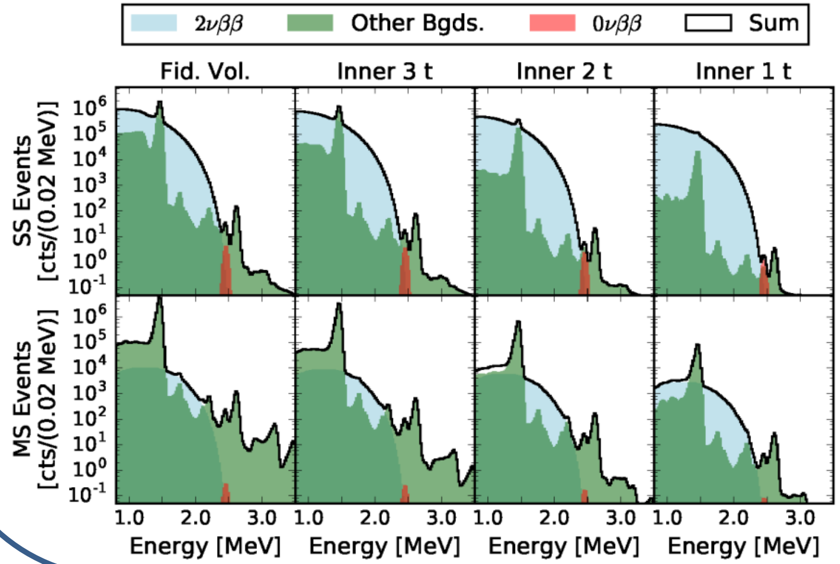
Moving forwards towards nEXO

LXe mass (kg)	Diameter or length (cm)	
5000	130	nEXO
150	40	EXO-200

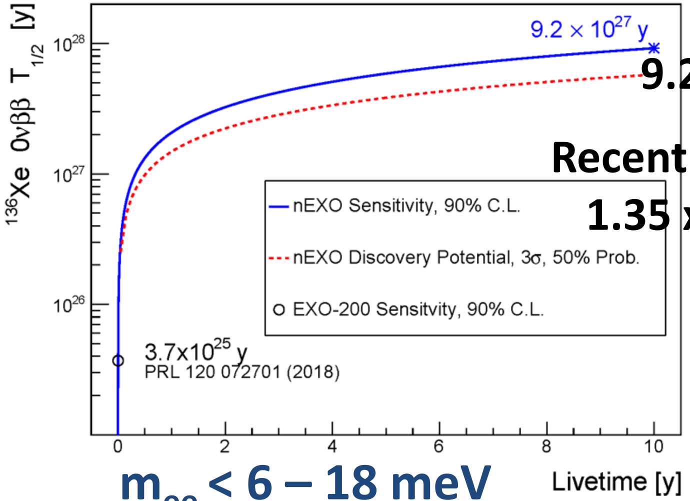
Improvement in light sensors (LAAPDs → SiPMs), light collection, cold electronics, radiopurity



Importance of fiducialization



Projected sensitivity of nEXO



9.2 x 10^{27} y

Recent upgrade

1.35 x 10^{28} y

$m_{ee} < 6 - 18$ meV

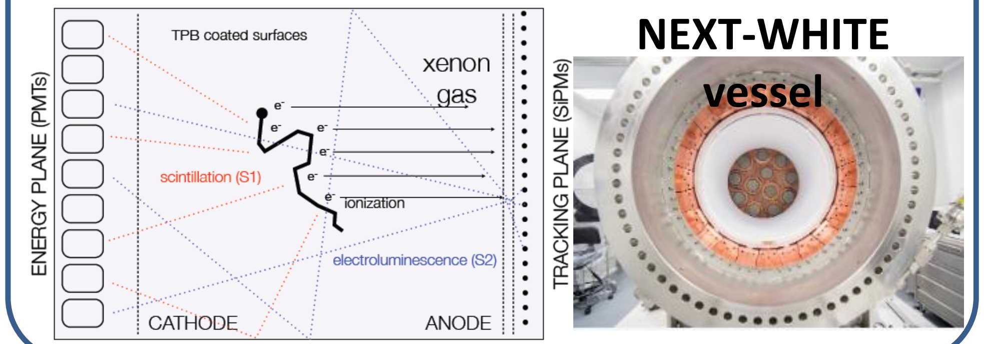
^{136}Xe

JHEP 05, 159 (2016)

NEXT

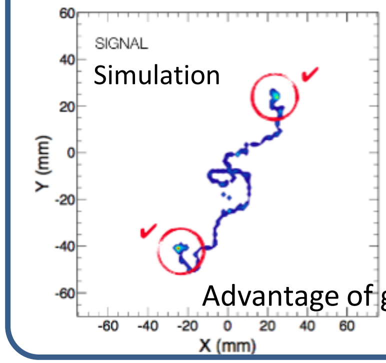
High pressure (10-15 bar) enriched Xe TPC

- Primary scintillation ($t_0 \rightarrow$ z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane)

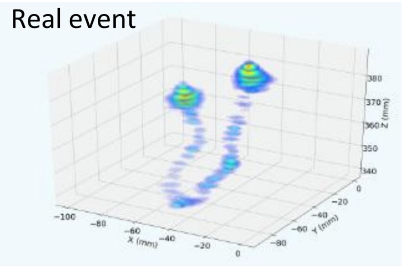


5 kg working prototype (NEXT-WHITE)

- **ΔE < 1% FWHM** in the ROI (< 25 keV)
- Very clear topological signature
- ^{136}Xe run since 2019 (2ν mode observed)



Canfranc – Spain



NEXT 100

Canfranc – Spain

- Many detector elements available
- Commissioning in 2022

3 y sensitivity: $T_{1/2} > 6\times10^{25}$ y

m_{ee} < 71 – 218 meV

Medium-term prospects – NEXT-1t

- Ton scale
- High definition tracks (add $He/CH_4/CF_4$)
- Si-PM instead of PM (better background)
- **10 y sensitivity: $T_{1/2} > 2.7\times10^{27}$**

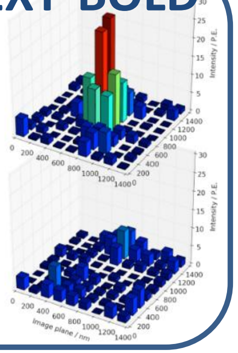
m_{ee} < 11 – 33 meV

Long-term prospects – NEXT-BOLD

Ba-tagging

Promising **detection of single Ba^{++} ions** by fluorescence imaging.

Results both by NEXT and nEXO

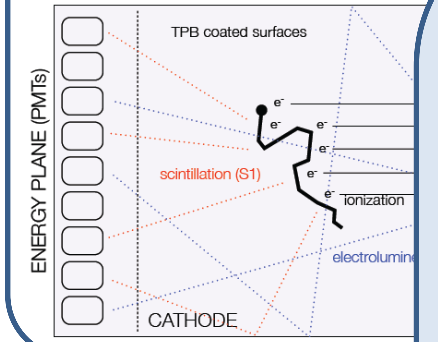


^{136}Xe

NEXT

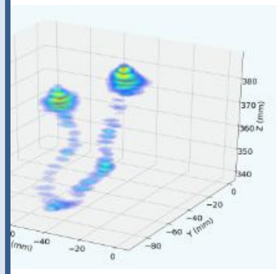
High pressure (10-15 bar) enriched Xe TPC

- Primary scintillation ($t_0 \rightarrow$ z coordinate)
- Electroluminescence fo[r energy resolution]
  (PMT plane) and fo



5 kg working prototype (NEXT-WHITE)

- **ΔE < 1% FWHM** in the ROI (< 25 keV)
- Very clear topological signature
- mode observed)
- anc – Spain



Other Xe-gas-TPC projects:

PANDA-X-III

- Two Micromega planes to read charge
- Xe + quencher
- Better space resolution wrt NEXT
- Worst energy resolution (by factor 3) wrt NEXT
- Difficult reconstruction of z coordinate
- Phased approach: 200 kg module (phase I)
  5 modules (ton scale) (phase II)

AXEL

Electroluminescence TPC as NEXT

- Cellular structure based on SiPMs

NEXT 100

- Many dete
- Commissio

6×10^{25} y

meV

Medium-term p

- Ton scale
- High definition
- Si-PM instead of
- **10 y sensitivity: $T_{1/2} > 2.7\times10^{27}$**

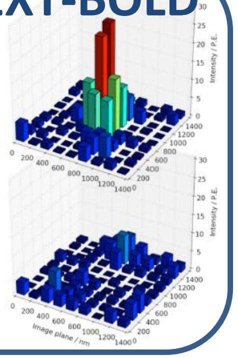
$m_{ee} < 11 – 33$ meV

NEXT-BOLD

le

imaging.

Results both by NEXT and nEXO

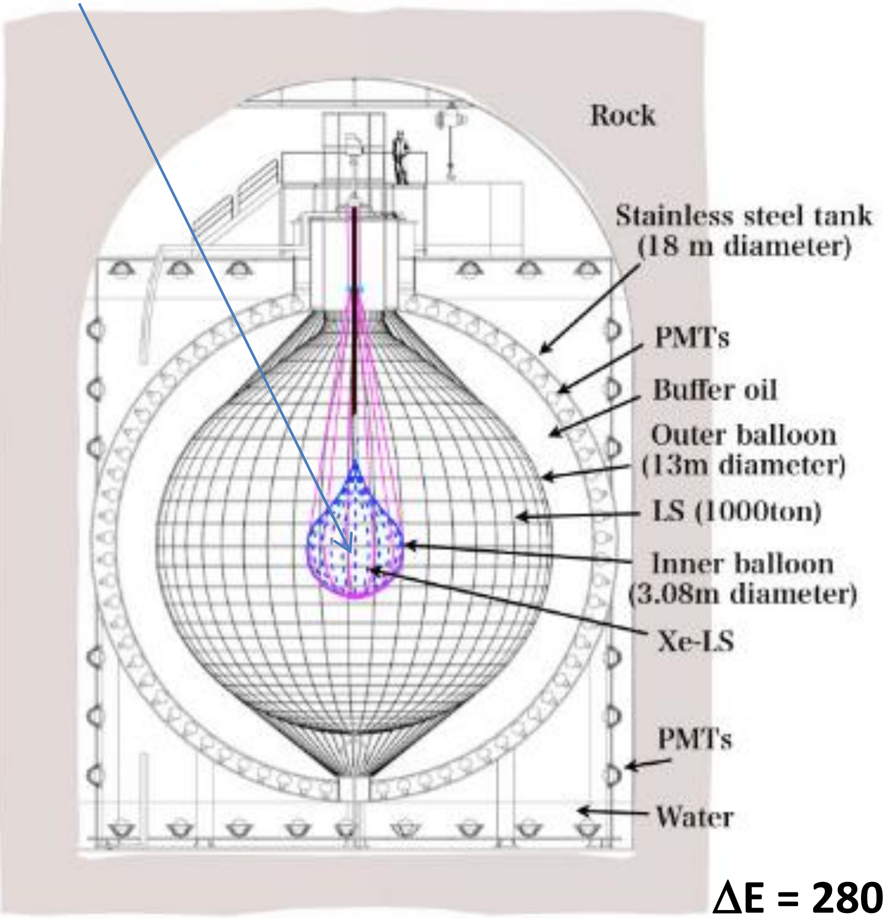


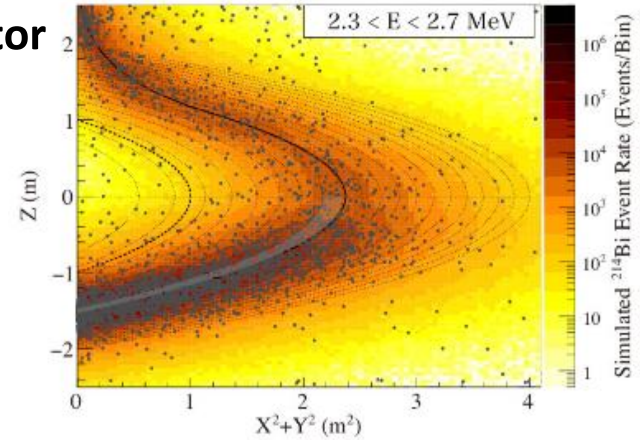
^{136}Xe KamLAND-Zen 400,800→KamLAND2-Zen

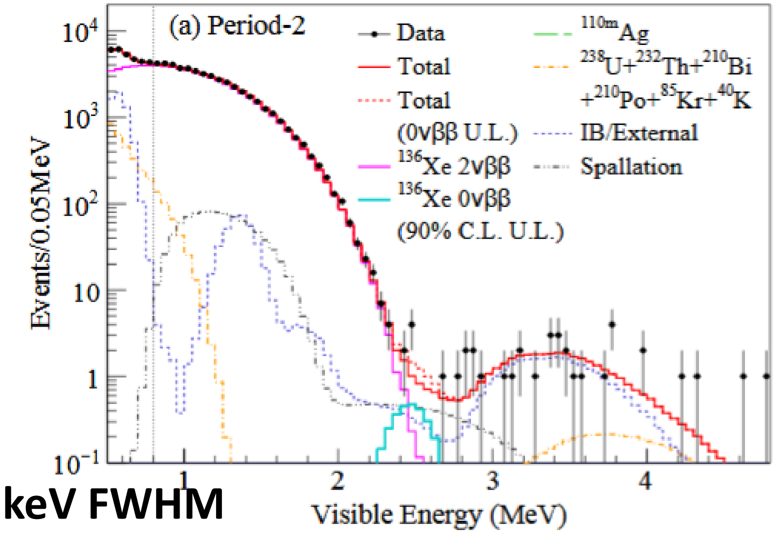
KamLAND-Zen 400: data taking completed
Kamioka – Japan **Leading experiment**

Results: $T_{1/2} > 1.07 \times 10^{26}$ y
$m_{ee} < 60 – 160$ meV

Enriched Xenon (350 kg) diluted in liquid scintillator







ΔE = 280 keV FWHM

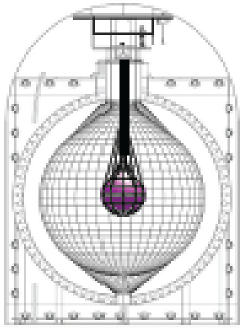
Phys. Rev. Lett. 117, 082503 (2016), arXiv:2104.10452

KamLAND-Zen 400,800→KamLAND2-Zen

KamLAND-Zen 400: data taking completed
Kamioka – Japan **Leading experiment**

Results: $T_{1/2} > 1.07\times10^{26}$ y
$m_{ee} < 60 – 160$ meV

Upgrade of KamLAND-Zen 400

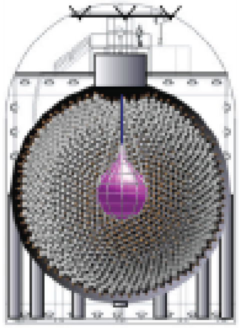


Present
KamLAND-Zen 800
~750 kg of Xenon
Data taking

Similar to KamLAND-400
Major new points:
- More isotope – **750 kg of ^{136}Xe**
- New balloon
- **$T_{1/2} > 4.6\times10^{26}$ y**

$m_{ee} < 26 – 80$ meV

New experiment → Substantiantial changes



Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution

Major new points:
- More isotope – **~1 ton of ^{136}Xe**
- Improve light collection
  Brighter liquid scintillator
  → ΔE_{FWHM}: 280 keV → **< 170 keV**
- Accomodate scintillating crystals
  → multi-isotope search

$m_{ee} < 20$ meV

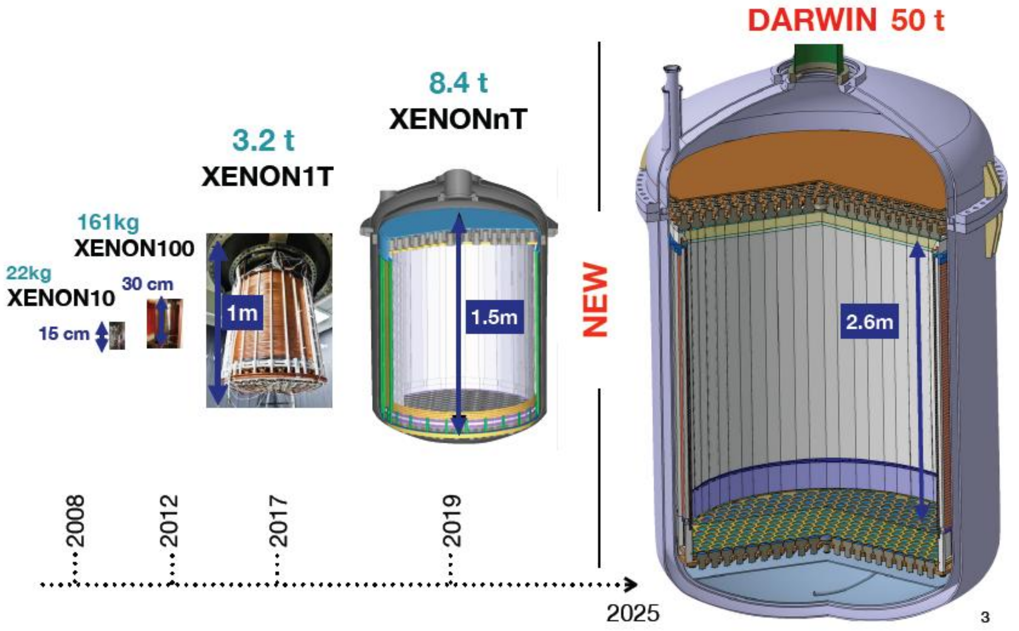
^{136}Xe

Eur. Phys. J. C 80, 808 (2020)

DARWIN as a neutrinoless double beta decay experiment

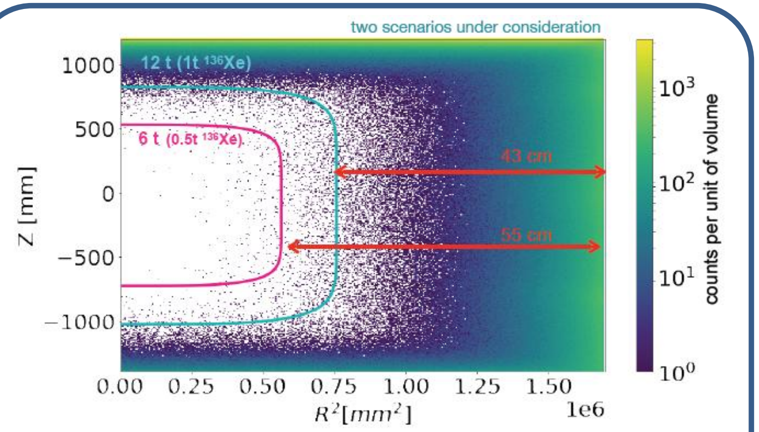
Dark matter + **double beta decay** + **other rare event searches**

LNGS, Italy



Dual-phase Time Projection Chamber (TPC)
50 t total (**40 t active**) of natural liquid xenon (LXe)

DARWIN will have more than **3.5 t** of active ^{136}Xe



Main background sources

- ^{222}Rn in LXe
- ^{137}Xe from μ-induced neutrons
- ^{8}B Solar neutrinos

Factor 10^4 reduction wrt XENON1T

10 y sensitivity: $T_{1/2} > 2.4\times10^{27}$ y
$m_{ee} < 11 – 35$ meV

^{130}Te

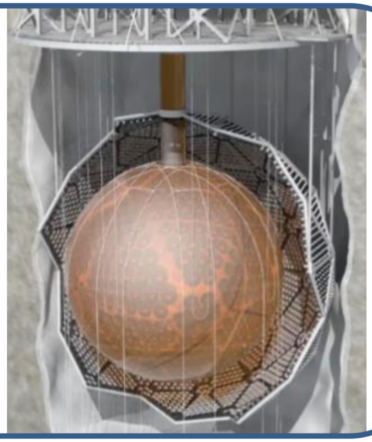
SNO+

arXiv:2104.11687

Re-use existing infrastructure of SNO at SNOLAB – Canada

SNO+ phase I: SNO acrylic vessel filled with LS and 1.3 tons of natural Te in an organometallic compound (0.5% mass loading)

- After ultrapure water phase, filling with LS is in progress
- **ΔE = 190 keV FWHM**
- **5 y sensitivity: $T_{1/2} > 1.9\times10^{26}$ y** **$m_{ee} < 30 – 104$ meV**



Possible SNO+ phase II (ongoing R&D)

- Increase Te concentration (**it does not affect background**)
- Increase light yield
- Improve transparency
- Improve light detectors

$T_{1/2} > 1\times10^{27}$ y

$m_{ee} < 13 – 45$ meV

Further evolution of this technology with new concepts: THEIA project

- 50 kton water-based liquid scintillator detector
- High coverage with fast photon detectors
- Deep underground
- 8-m radius balloon with high-LY LS and isotope
- 7-m fiducial, 3% ^{nat}**Te**, 10 years
- **Dominant background: ^{8}B solar ν's $\rightarrow$ directional measurement**

$T_{1/2} > 1.1\times10^{28}$ y

$m_{ee} < 4 – 14$ meV

without enrichement

^{76}Ge

GERDA, MAJORANA → LEGEND

GERDA *Phys. Rev. Lett. 125, 252502 (2020)*

Exposure: 103.7 kg × y

Background index: **$5.2^{+1.6}_{-1.3}$ × 10^{-4} c/(keV kg y)**

$T_{1/2}$ > 1.8×10^{26} y

m_{ee} < 79 – 180 meV

MAJORANA demonstrator

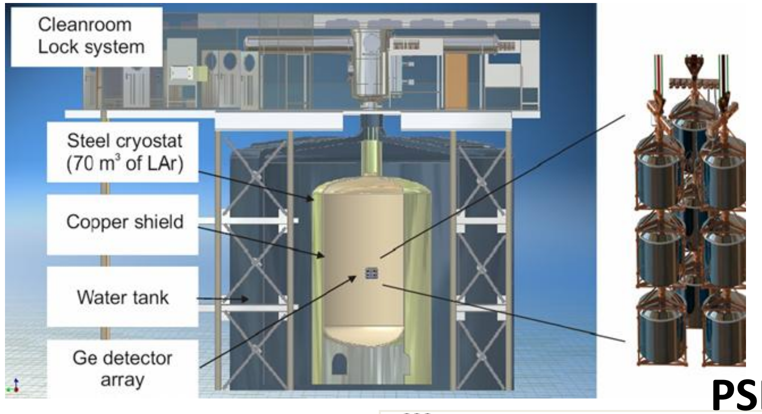
Exposure: 26 kg × y

Background: **(4.7±0.8) × 10^{-3} c/(keV kg y)**

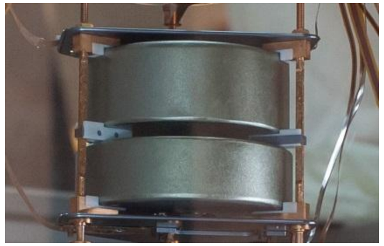
$T_{1/2}$ > 2.7×10^{25} y

m_{ee} < 204 – 465 meV *Phys. Rev. C 100, 025501 (2019)*

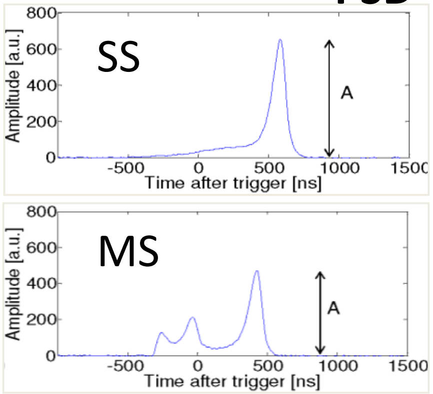
37 HP Ge diodes immersed in LAr



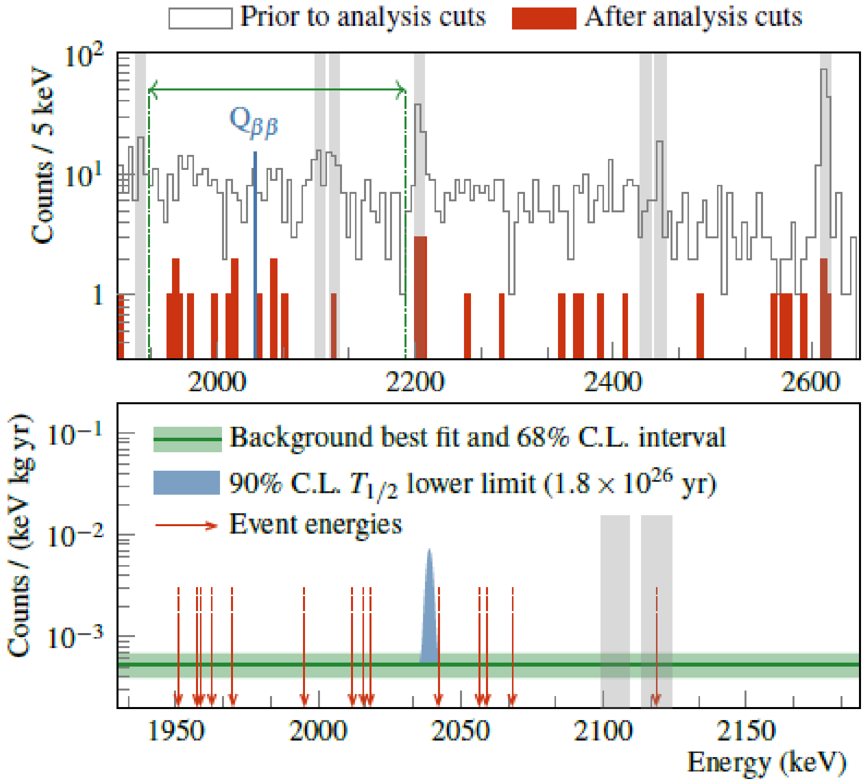
35 kg of enriched Ge



PSD



ΔE = 3 keV FWHM



^{76}Ge

GERDA, MAJORANA → LEGEND

GERDA
Exposure: 103.7 kg × y
Background index: **$5.2^{+1.6}_{-1.3} \times 10^{-4}$ c/(keV kg y)**
$T_{1/2} > 1.8\times10^{26}$ y
$m_{ee} < 79 – 180$ meV

MAJORANA demonstrator
Exposure: 26 kg × y
Background: **$(4.7\pm0.8) \times 10^{-3}$ c/(keV kg y)**
$T_{1/2} > 2.7\times10^{25}$ y
$m_{ee} < 204 – 465$ meV

Combining the best of MAJORANA and GERDA → LEGEND

MAJORANA:
- Radiopurity of parts near detectors (FETs, cables, Cu mounts, etc.)
- Low noise electronics → better pulse-shape discrimination
- Low energy threshold → improved cosmogenic background rejection

GERDA:
- LAr veto
- Low-A shield, no Pb

Both

- Clean fabrication techniques
- Control of time on surface to reduce cosmogenic backgrounds
- Development of large point-contact detectors

Mission of LEGEND: discovery potential at a half-life **1.3×10^{28} y**
$m_{ee} < 9 – 21$ meV

AIP Conference Proceedings 1894, 020027 (2017)

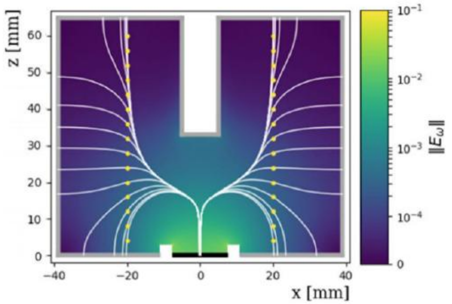
LEGEND

LEGEND-200:

LNGS – Italy

- Initial Phase
- **~200 kg** in upgraded existing GERDA infrastructure
- **Improvements**:
  - LAr optical purity (light yield, attenuation)
  - Light detection (add readout between detector strings)
  - Cleaner materials and smaller parts near detectors
  - Larger detectors (fewer cables, readout channels)
  - Surface betas (^{42}Ar progeny): Reduce LAr volume and improve pulseshape
  - Discrimination (better electronics)
  - **New inverted-coaxial larger detectors (1.5 – 2 kg)** →
- **Background goal**: **2×10^{-4} c/(keV kg y)**
- **Commissioning to be started in November 2021**
- **Sensitivity: > 10^{27} y for 1 tonne × y** **m_{ee} < 34 – 78 meV**

ICPC detector geometry



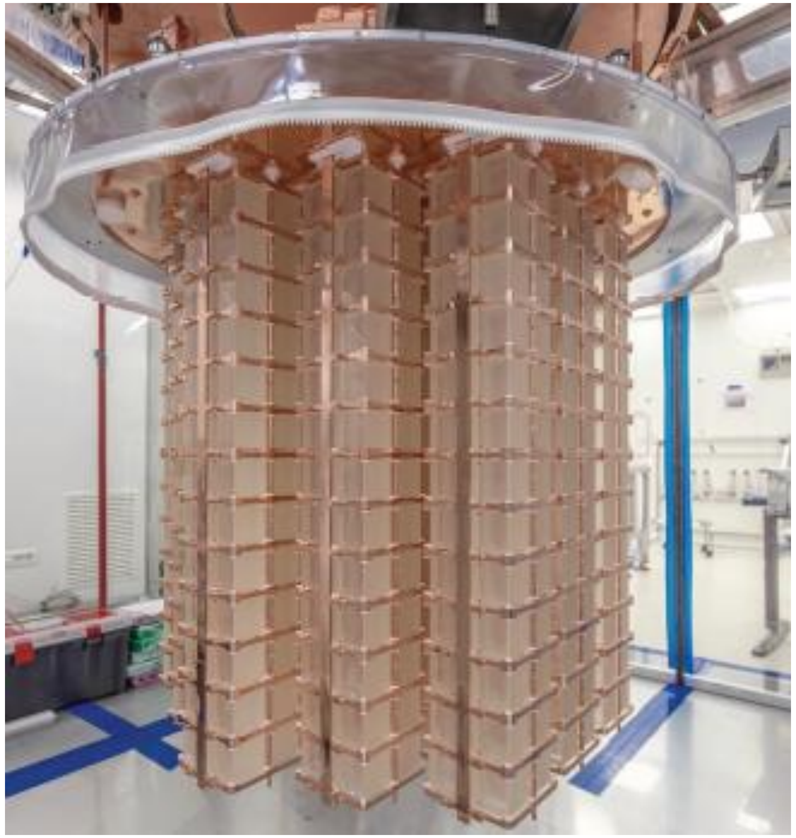
LEGEND-1000:

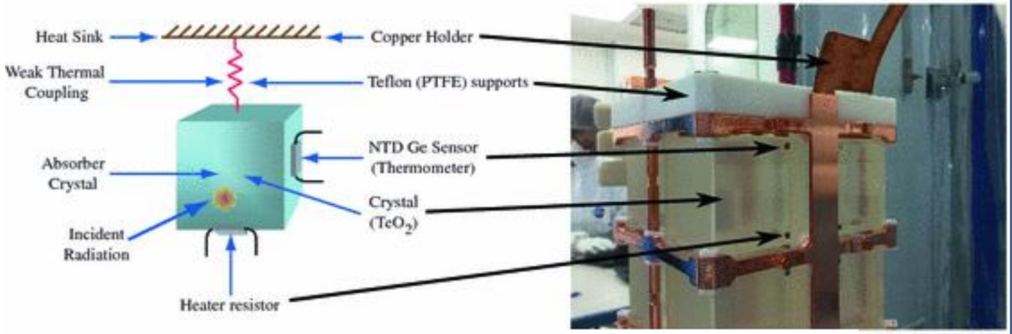
- **1000 kg (phased)** required to cover neutrino-mass IH
- **Half-life discovery sensitivity: 1.3×10^{28} y**
- Background goal: **10^{-5} c/(keV kg y)** → **background free at 10 ton × y**
- Location under discussion (SNOLAB or LNGS)
- Required depth under investigation

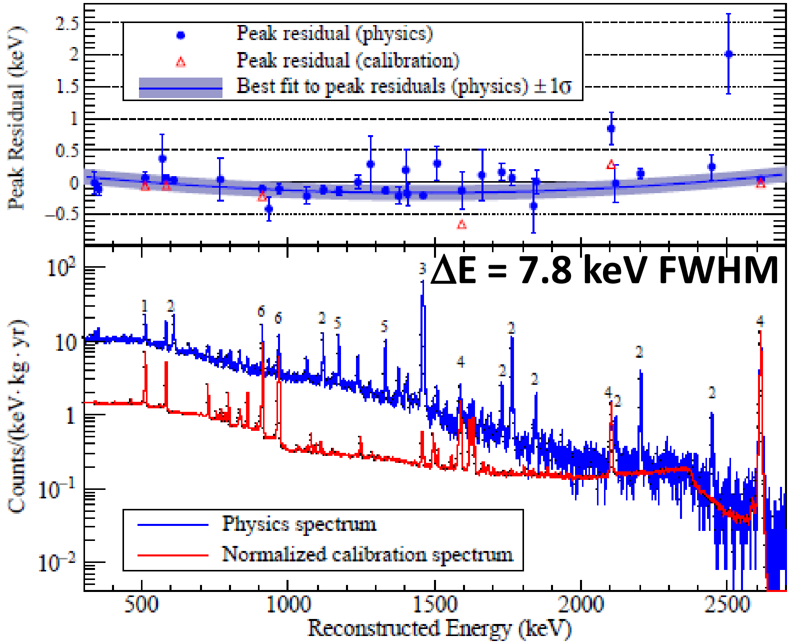
CUORE

arXiv:2104.06906

988 TeO_2 bolometers, arranged in 19 towers, cooled down to 10-15 mK in LNGS (Italy)
evolution of Cuoricino - **741 kg** with natural tellurium – **206 kg of ^{130}Te**







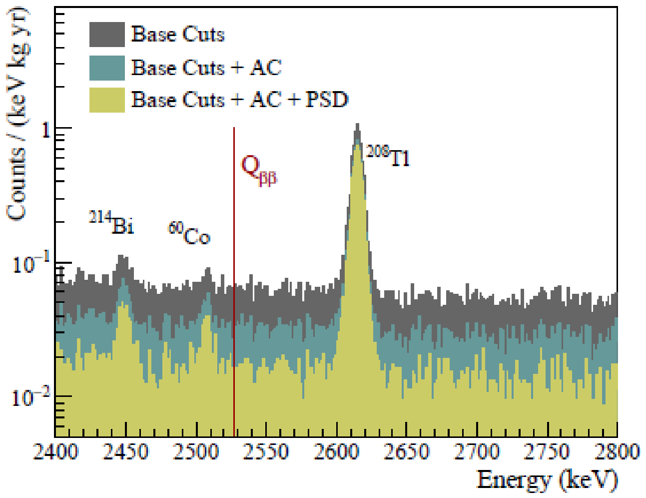
arXiv:1907.09376

CUORE → CUPID

LNGS – Italy

CUORE is collecting data succesfully

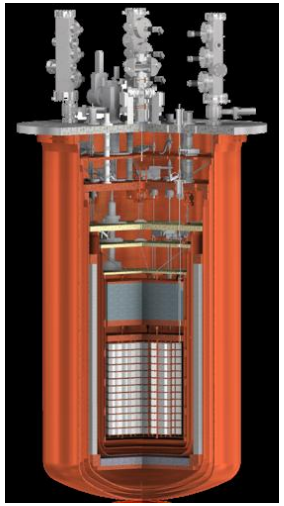
- Exposure: **1038.4 kg × y - $T_{1/2}$ > 2.2×10^{25} y**
  m_{ee} < 90 – 305 meV
- Background close to expectations:
  b = 1.4 × 10^{-2} c/(keV·kg·yr)
  dominated by energy-degraded surface α particles
- 5 y projected half-life sensitivity: **~10^{26} y**
  m_{ee} < 42 – 143 meV



Three important messages from CUORE

1. **A tonne-scale bolometric detector is feasable**
2. **An infrastructure to host a bolometric next-generation 0νββ experiment is already available**
3. **The analysis of ~1000 individual bolometers is handable**

CUPID is the natural evolution of CUORE



^{82}Se, ^{100}Mo

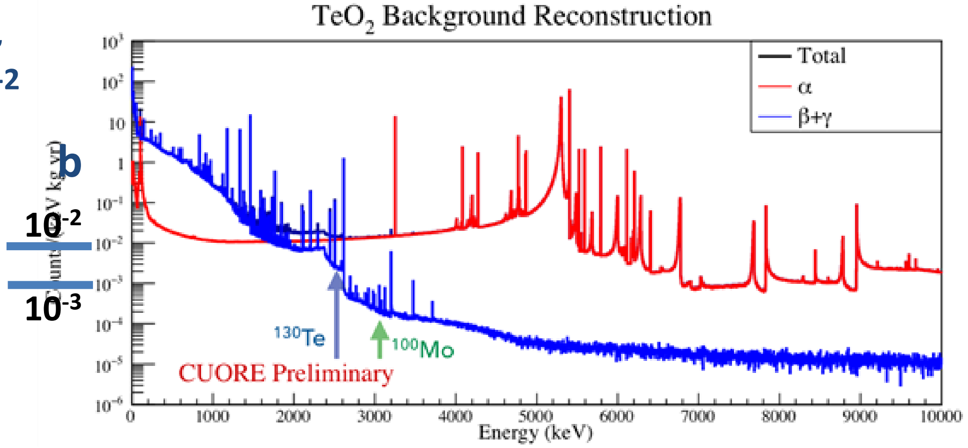
CUPID demonstrators

CUORE background presently dominated by α particles from surface contamination → b=10^{-2}

Secondly, external γ background → b=10^{-3}

Moving to CUPID requires:

0. Enrichment
1. Rejection of surface alphas
2. Limitation of the residual γ background



→ New detector technology: **scintillating bolometers** → **R&D and demonstrators**

→ **Isotopes with Q-value > 2615 keV**

^{82}Se in scintillating ZnSe crystals → demonstrator **CUPID-0** (ex LUCIFER erc)

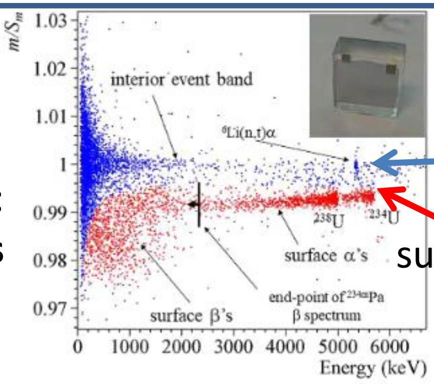
^{116}Cd in scintillating $CdWO_4$ crystals → R&D in LSM (Modane) and LSC (Canfranc)

^{100}Mo in scintillating Li_2MoO_4 crystals → demonstrator **CUPID-Mo**(ex LUMINEU)

TeO_2
Li_2MoO_4

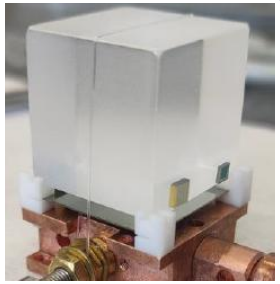
CROSS erc
Canfranc

Less mature but resolving alternative: reject **surface events** by **PSD assisted by metal film coating**



BINGO erc
Modane

- Internal active shield ($ZnWO_4$ scintillators)
- Enhanced-sensitivity light detectors
- Revolutionary detector mechanics against surface radioactivity



^{82}Se, ^{100}Mo

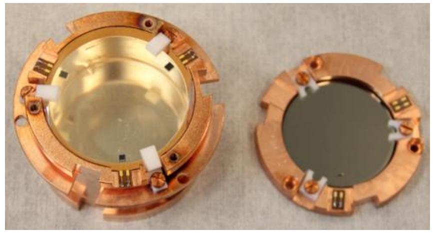
CUPID demonstrators

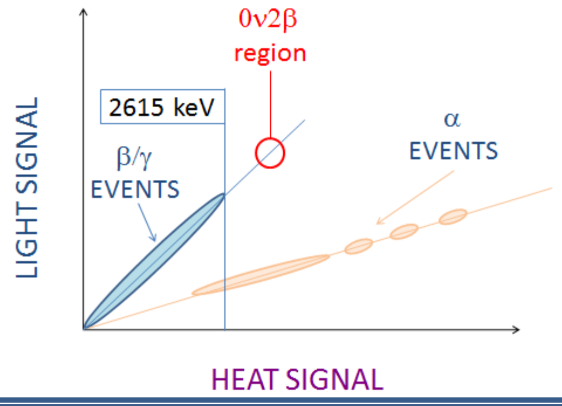
Scintillating bolometers

α particle rejection

Exploit lower light yield of α wrt β/γ (typically 20%)

Main crystal   Light detector





CUPID-0 – $Zn^{82}Se$ Q=2998 keV

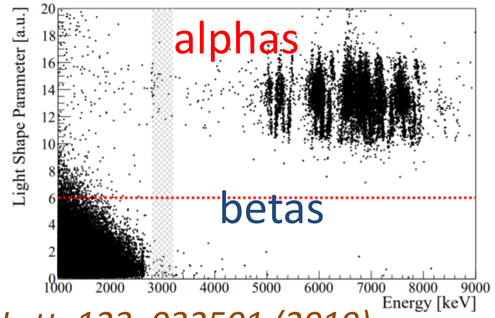
First running demonstrator - LNGS

24 crystals – 5.28 kg ^{82}Se

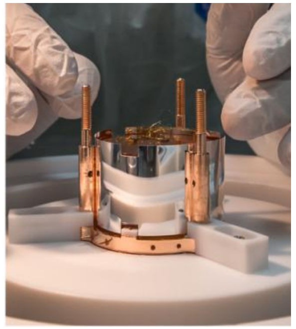
Best limit on ^{82}Se: **$T_{1/2}$ > 3.5×10^{24} y**

Energy resolution: **~23 keV FWHM**

Required improvements in crystal quality and radiopurity



Phys. Rev. Lett. 123, 032501 (2019)



Evolution of LUCIFER

LNGS – Italy

b = 3.5 × 10^{-3} c/(keV·kg·yr)

CUPID-Mo – $Li_2{}^{100}MoO_4$ Q=3034 keV

20 crystals – 2.34 kg ^{100}Mo

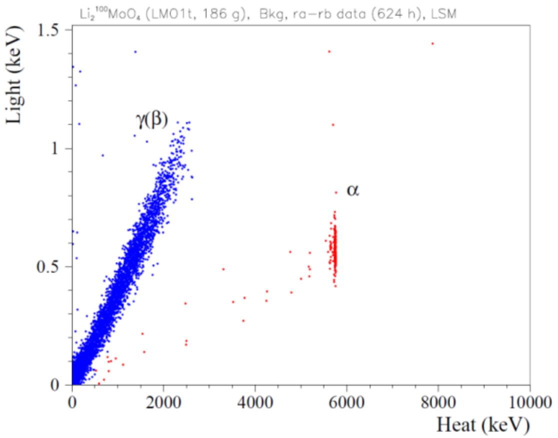
Data taking concluded but analysis ongoing

Energy resolution: **~5 keV FWHM**

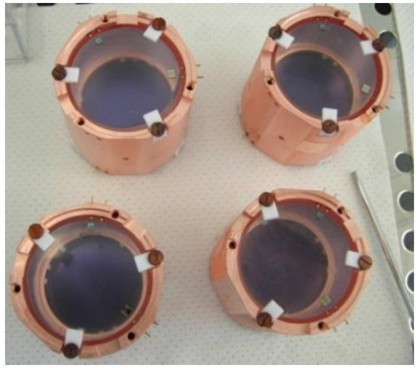
Radiopure high-quality crystals

Negligible ^{100}Mo losses in crystal growth

- Zero background
- Best worldwide limit on ^{100}Mo



Modane – France



^{82}Se, ^{100}Mo

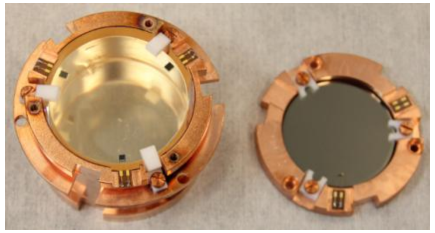
CUPID demonstrators

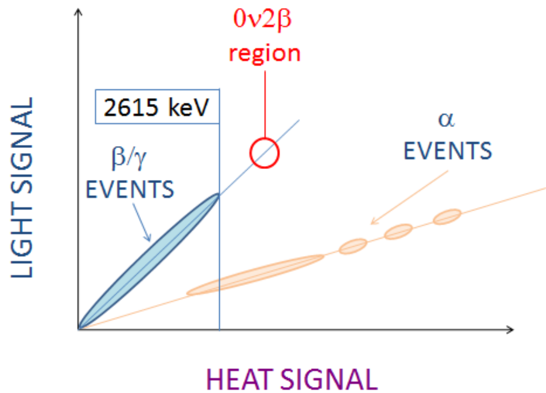
Scintillating bolometers

α particle rejection

Exploit lower light yield of α wrt β/γ (typically 20%)

Main crystal   Light detector





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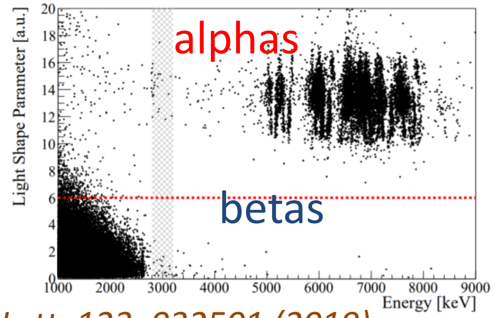
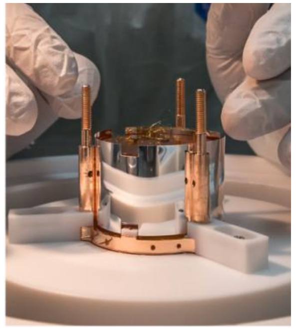


Phys. Rev. Lett. 123, 032501 (2019)



Evolution of LUCIFER

LNGS – Italy

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CUPID-Mo – $Li_2{}^{100}MoO_4$ Q=3034 keV

20 crystals – 2.34 kg ^{100}Mo

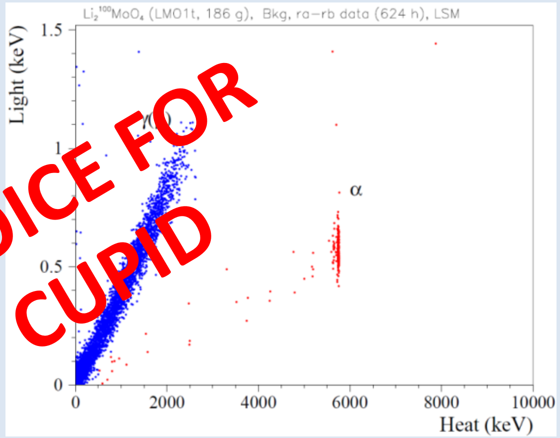
Data taking concluded but analysis ongoing

Energy resolution: **~5 keV FWHM**

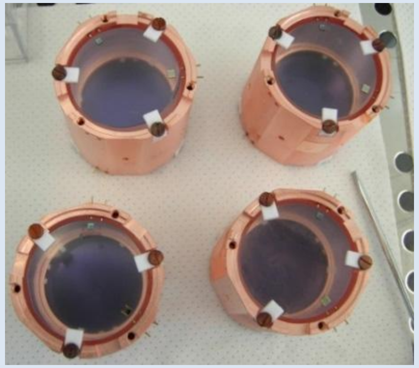
Radiopure high-quality crystals

Negligible ^{100}Mo losses in crystal growth

- Zero background
- Best worldwide limit on ^{100}Mo



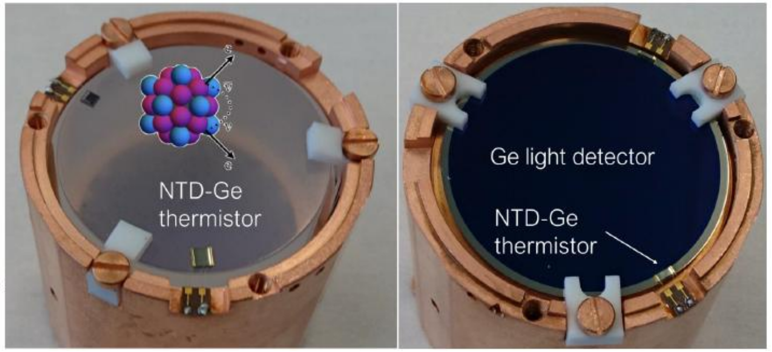
Modane – France

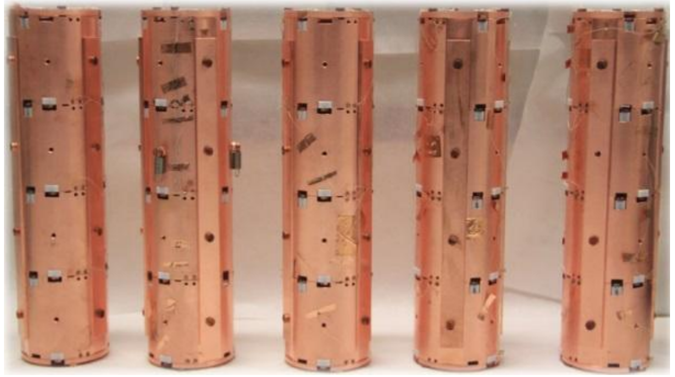


CUPID-Mo

Phys. Rev. Lett. 126, 181802 (2021)

- High-sensitivity search for double beta decay of ^{100}Mo
- Installed in the **Modane** underground laboratory (France)
- It has coexisted in the same cryostat as the EDELWEISS dark matter experiment
- Regular data taking during April 2019 – July 2020
- Evolution of **LUMINEU** and demonstrator for **CUPID**

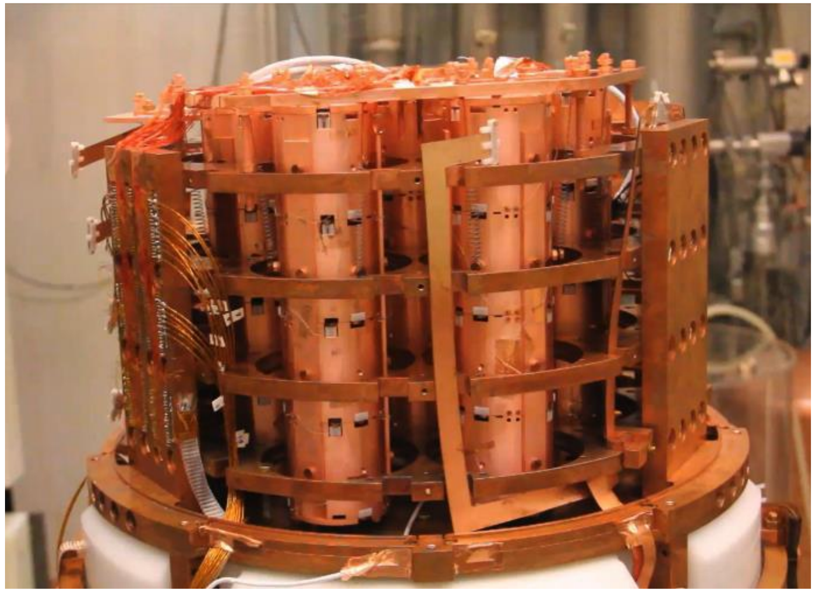




20 x 0.2-kg crystals of $Li_2{}^{100}MoO_4$

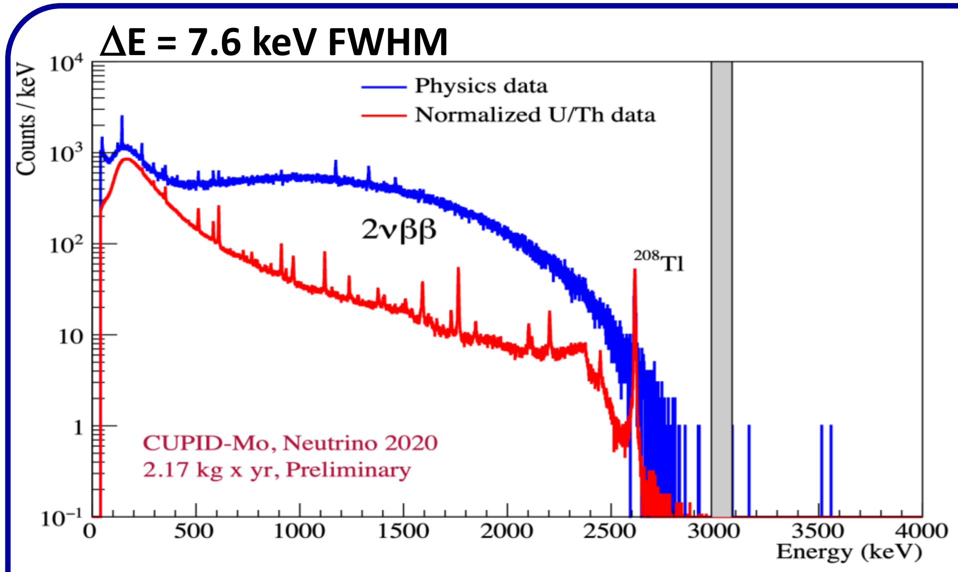
2.26 kg ^{100}Mo

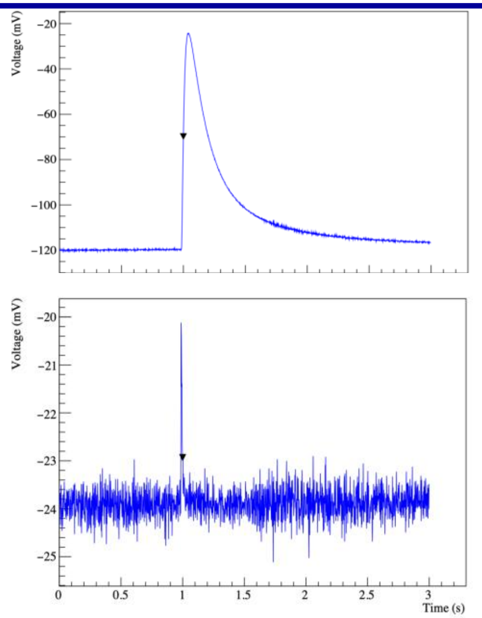
20-scintillating-bolometer array



^{100}Mo

CUPID-Mo

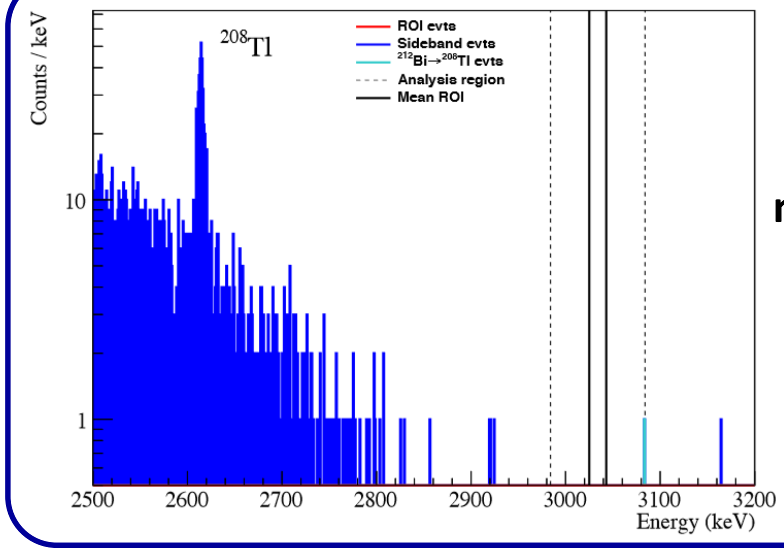




Heat-light coincidence

Heat signal

Light signal



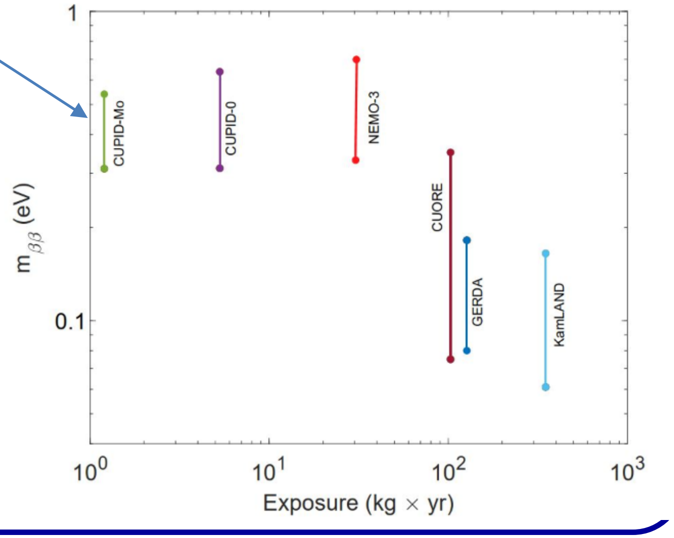
Exposure: 1.17 kg x d

$T_{1/2} > 1.5 \times 10^{24}$ y

$m_{ee} < 310 - 540$ meV

Zero background in the region of interest

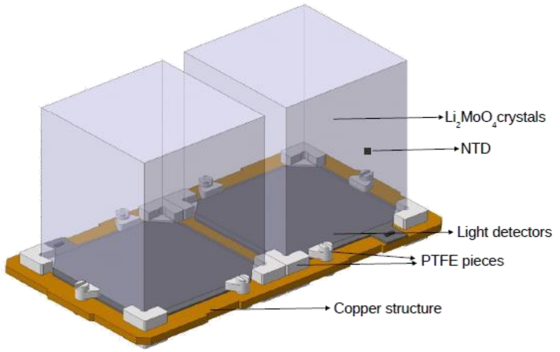
b = [2 – 6] x 10^{-3} counts/(keV kg y)



^{100}Mo

CUPID configuration and reach

- Single 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
- No reflecting foil
- Ge light detector as in CUPID-Mo, CUPID-0



b ~ 10^{-4} counts/(keV kg yr) in the ROI of ^{100}Mo (~ 3 MeV) with $Li_2{}^{100}MoO_4$ crystals supported by detailed Monte Carlo combining CUORE, CUPID-Mo and CUPID-0.
Limitation: **random coincidences of 2ν2β events**

CUPID 10 y half-life sensitivity:

$T_{1/2}$ > 1.5 × 10^{27} y

m_{ee} < 10 – 17 meV

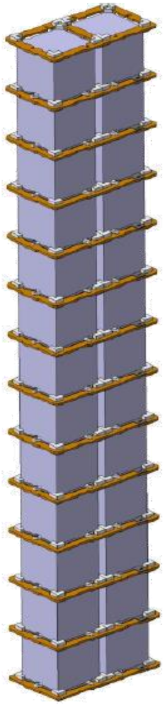
CUPID-reach - Bkg improvement by factor 5

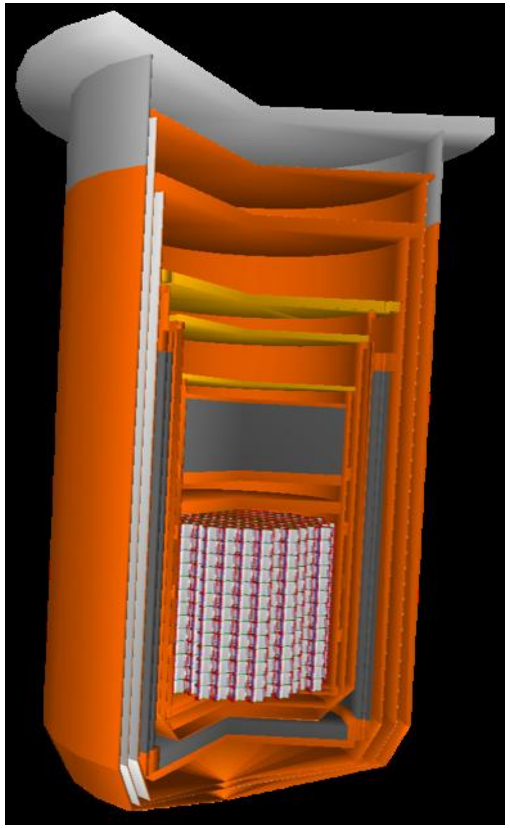
2.3 × 10^{27} y → **m_{ee} < 7.9 – 14 meV**

CUPID-1 T - Bkg improvement by factor 20

1 ton isotope → new cryostat

9.2 × 10^{27} y → **m_{ee} < 4.0 – 6.9 meV**





^{100}Mo

AMoRE

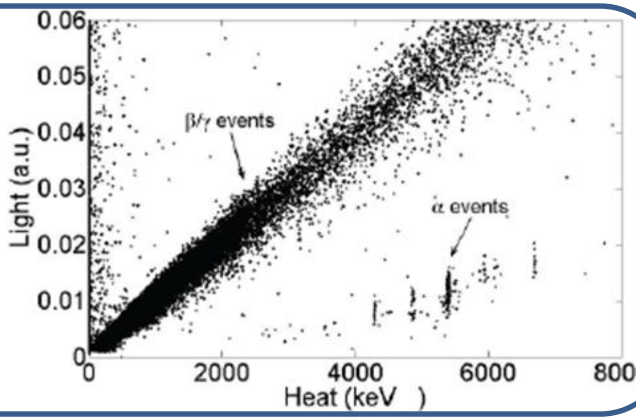
2020 JINST 15 C08010

Detector concept

scintillating bolometers based on **$Ca^{100}MoO_4$ (AMoRE-pilot)**

Ca is depleted from ^{48}Ca to avoid ^{48}Ca- $2\nu\beta\beta$ background

Moving to Li_2MoO_4 for final phase

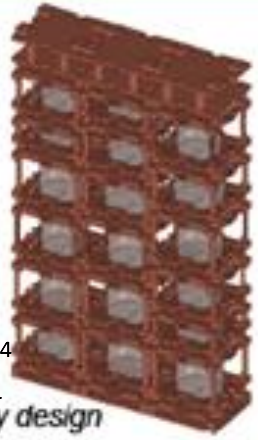


- AMoRE-I at Y2L (same cryostat as Pilot), with $CaMoO_4$ crystals + a few others (ZMO, LMO, …)
- AMoRE-II at a new, larger laboratory (ARF), $X^{100}MoO_4$ crystals (X = Li, Na, ^{40}Ca, Zn or other)

Korea

AMoRE-Pilot
~1.8 kg
2015-2018
6x $Ca^{100}MoO_4$ crystals

AMoRE-I
5~6 kg
Running
13x $Ca^{100}MoO_4$
6x $Li_2{}^{100}MoO_4$
Preliminary design



AMoRE-II
200 kg
Start
2022-2023

Enrichment is funded

Preliminary design

Target sensitivities: **10^{25} y** **5×10^{26} y**

m_{ee} < 120 – 210 meV **m_{ee} < 17 – 30 meV**

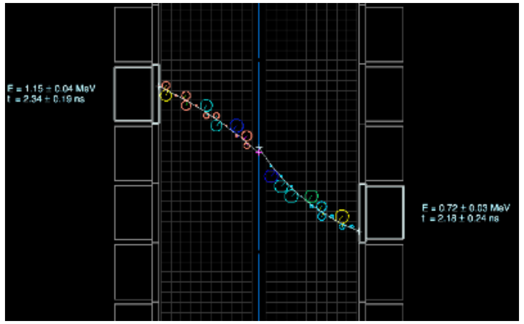
source ≠ detector

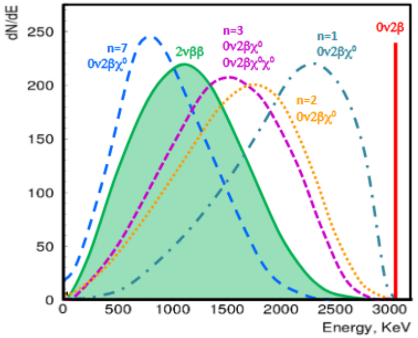
NIM A958, 162115 (2020)

SuperNEMO

- The most important of the few experiments with **detector ≠ source**
  The isotope is embedded in thin foils (difficult scaling – low efficiency ~30%)
- Built on the succesfull **NEMO-3 experiment**
- **Main advantage**: **full topological reconstruction of a ββ event**

Investigation of the **mechanism** → crucial task in case of discovery
Easier access to other physics channels (i.e. **Majoron**)





SuperNEMO demonstrator will start soon data taking – 7 kg of ^{82}Se **LSM – France**

Sensitivity: **6×10^{24} y** in **2.5 y** (assuming that the target radiopurity in ^{214}Bi and ^{208}Tl of the source foils is achieved)

Prospects

- The idea to build full SuperNEMO (20 module – 100 kg) is abandoned
  non competitive in the current scenario
- Plans to move to **^{150}Nd** – enrichment by centrifugation is expensive but now possible
  higher phase space by a factor 6 – Rn free background
- Keep technology ready in case of discovery

How to reach the few meV scale

80 000 bolometers of TeO_2 (natural isotopic composition)

20 dilution refrigerators with experimental space 4 x wrt CUORE

→ can be hosted by an LNGS hall

Mass of each crystal: 1.3 kg (6×6×6 cm)

Efficiency: 90%

Energy resolution: 5 keV FHWM

} Already achieved

Background index: b = 10^{-5} counts/(keV kg y) (testable in CUPID)

Live time: 10 y

90% sensitivity:

$T_{1/2} > 7 \times 10^{28}$ y

$m_{ee} < 1.6 – 7.5$ meV