
*September 8th, 2019*

# Neutrinoless double beta decay Experiments

*Andrea Giuliani*

# Outline

- Double beta decay: what it is and why it is important
- How we search for neutrinoless double beta decay
- Overview of the current experimental situation
- Details of the most important experiments
- Challenges for the future

# Outline

- Double beta decay: what it is and why it is important
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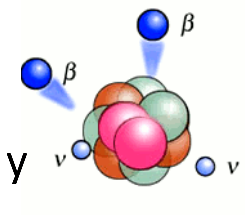
# What is double beta decay?

Two decay modes are usually discussed:

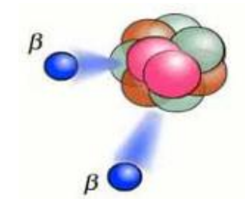
① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{19} - 10^{21}$ y




② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Neutrinoless
Double Beta Decay (0ν2β)
never observed $\tau > 10^{24} - 10^{26}$ y




Processes ② would imply new physics beyond the Standard Model

violation of total lepton number conservation (**LNV**)

It is a very sensitive test to new physics since the phase space term is much larger for process ② than for process ①

Interest for 0ν-DBD lasts for **70 years** !

**Goeppert-Meyer proposed the standard process in 1935**

**Furry proposed the neutrinoless process in 1939**

# Double beta decay and basic nuclear physics

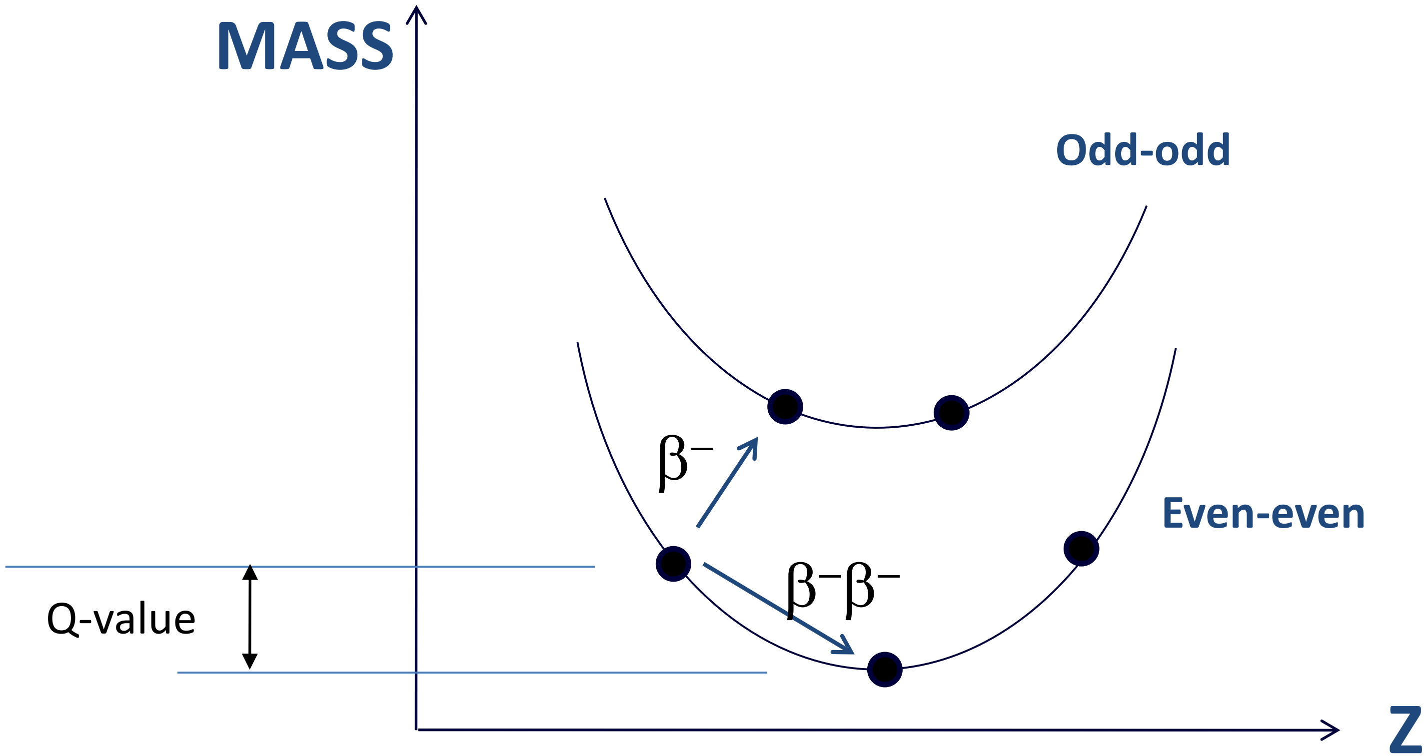
**Weiszaecker's formula for the binding energy of a nucleus**

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

Even-even

Odd-odd

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



# Double beta decay and basic nuclear physics

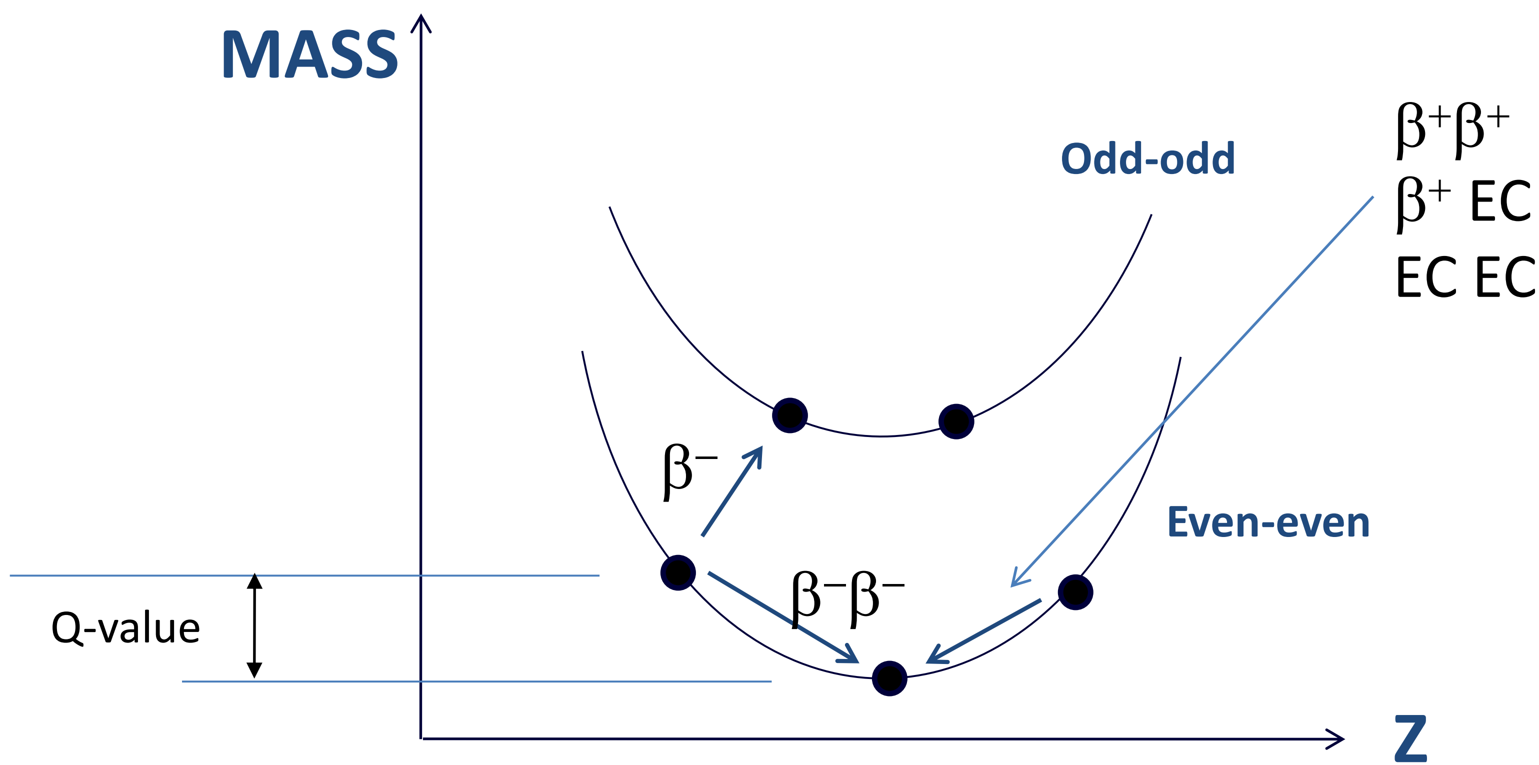
**Weiszaecker's formula for the binding energy of a nucleus**

**Even-even**

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

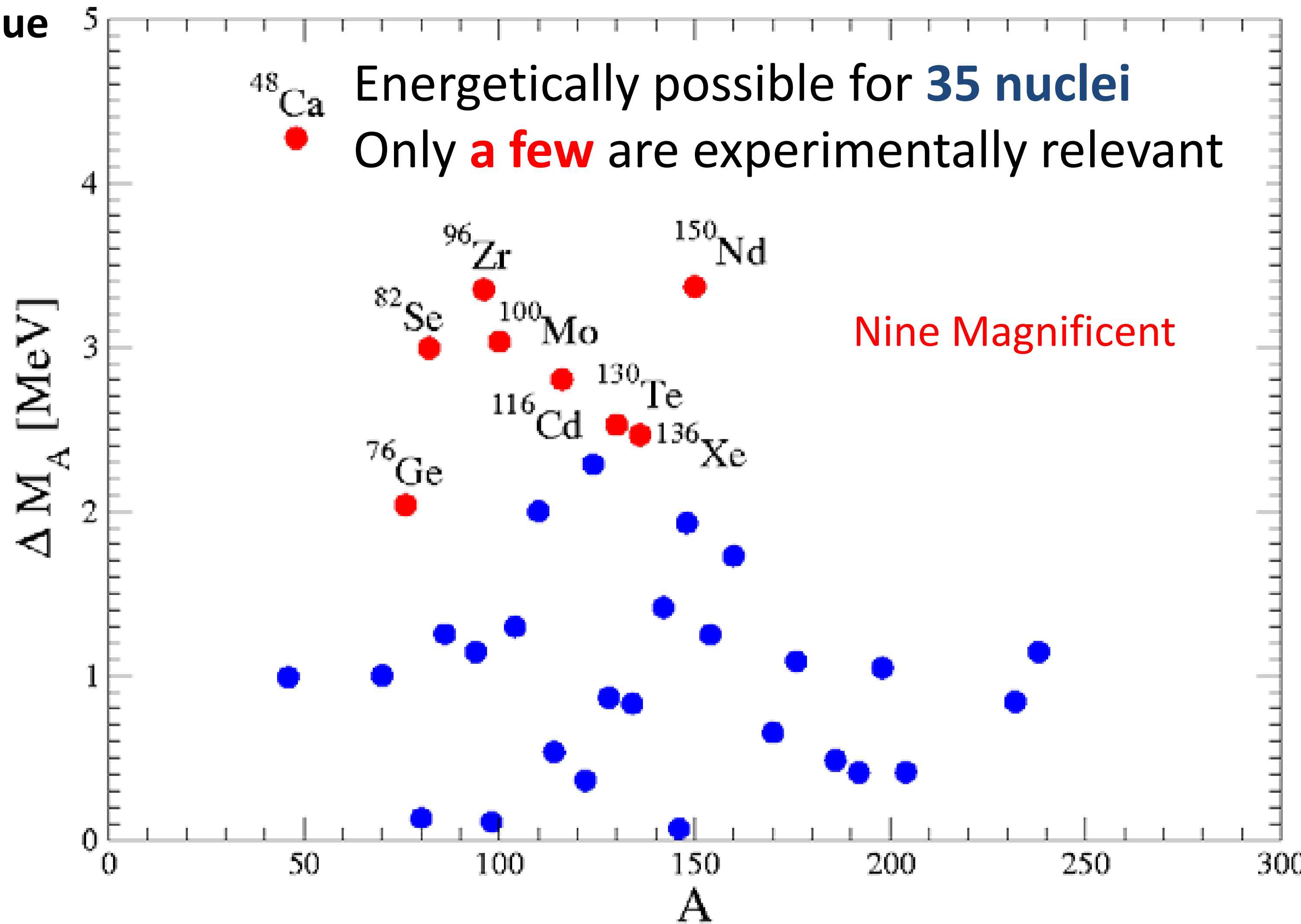
**Odd-odd**

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



# 35 nuclei can undergo double beta decay

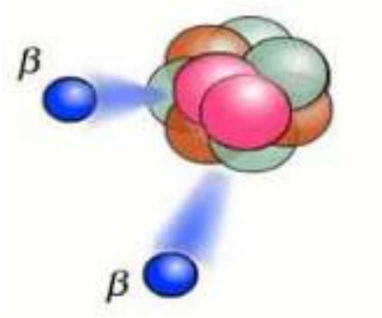
**Q-value**



# Neutrinoless double beta decay ($0\nu2\beta$): standard and non-standard mechanisms

$0\nu2\beta$ is a test for « creation of leptons »: **$2n \rightarrow 2p + 2e^-$ $\Rightarrow$ LNV**

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




$0\nu2\beta$

Standard mechanism: **neutrino physics**

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

**C. Giunti**

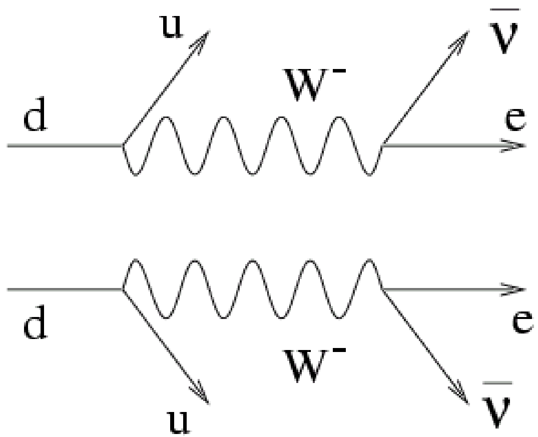
Non-standard mechanism: **Sterile $\nu$, BSM, LNV**

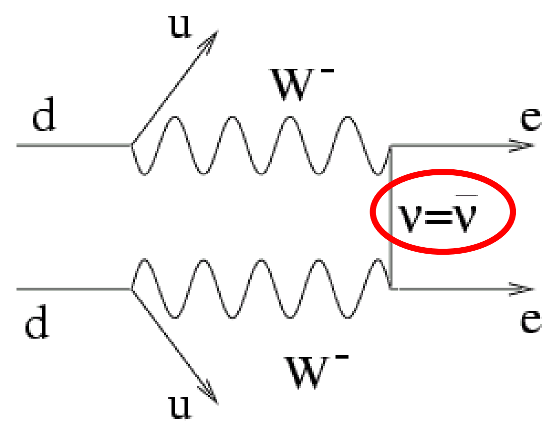
Not necessarily neutrino physics

# Double beta decay and neutrino physics

Double beta decay is a **second order weak transition** ← **very low rates**

Diagrams for the two processes discussed above:

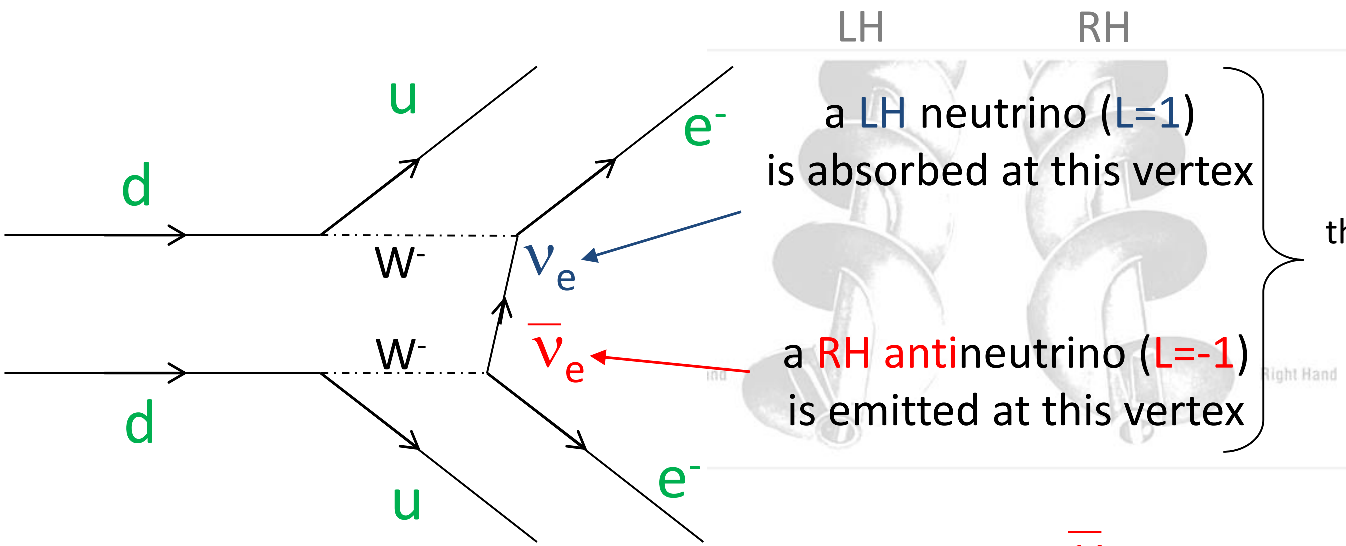



Standard-Model allowed process
**two "simultaneous" beta decays**

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

# Double beta decay and neutrino physics




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

**S. Bilenky**

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

- 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**

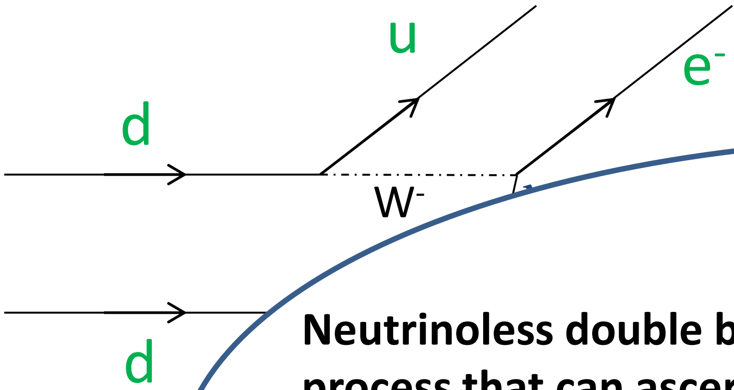
$\bar{\nu} = \nu$

- 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**

# Double beta decay and neutrino physics




LH RH

a LH neutrino (L=1)
is absorbed at this vertex

in pre-oscillations
standard particle physics
(massless neutrinos),
the process is forbidden because
...rino has not the correct
...lepton number
...rbed
...ertex

**Neutrinoless double beta decay is the only experimentally viable process that can ascertain the Majorana nature of neutrinos:**

- New form of matter: Majorana fermions
- Naturally incorporated in Grand Unification Theories
- Explain smallness of neutrino masses
- Can explain matter / antimatter asymmetry in the Universe

**P. Di Bari**

- IF neutrino...

  **Helicities** can be...
  **BUT** Lepton number is rig...

**0ν-DBD is forbidden**

$\bar{\nu} = \nu$

- 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**

DIRAC or MAJORANA
nature of neutrinos

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

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


Il Nuovo Cimento, **14** (1937) 171

# 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.*

DIRAC or MAJORANA

nature of neutrinos

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

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


Il Nuovo Cimento, **14** (1937) 171

# TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - ...

*"non vi è più nessuna ragione di presumere l'esistenza di [...] antineutrini"*
(*"**there is now no need to assume the existence of antineutrinos**"*).

# Neutrino flavor oscillations

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

Flavor eigenstates $\neq$ Mass eigenstates

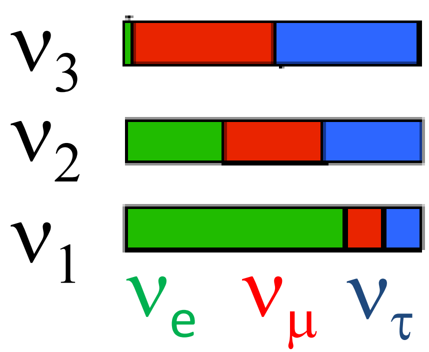
Weak interaction — Propagation

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

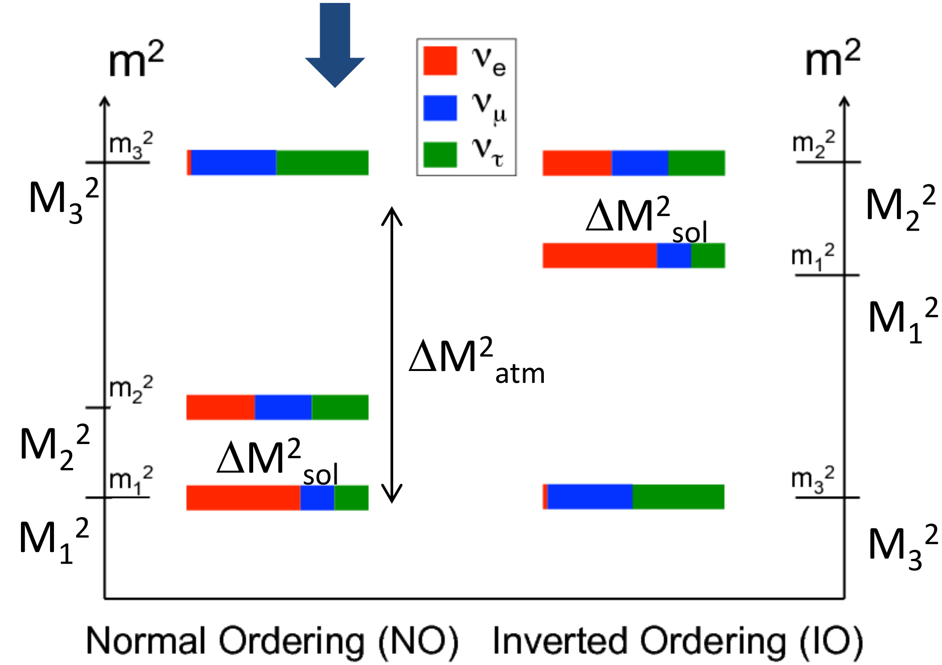
Neutrino flavor oscillations

## Neutrino mixing matrix (PMNS)

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



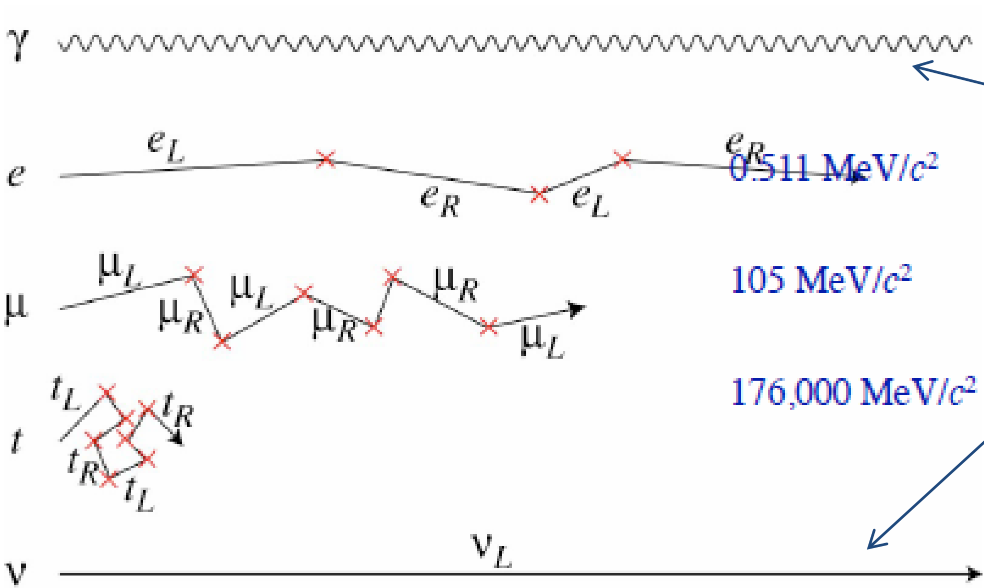

## Neutrino mass ordering



# In the Standard Model, neutrinos are massless

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

**M**




**Origin of the charged fermion masses in the Standard Model**

Particles bump on the Higgs field pervading all the empty space and acquire a mass

- **Photons** do not have a mass because they are neutral and do not interact with the Higgs field
- **Neutrinos** do not have a mass because they do not have a right-handed component and the left-handed component propagate freely

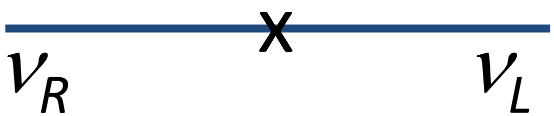
# Giving masses to neutrinos

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 $\boldsymbol{\nu_R}$ are new fields insensitive to the gauge interactions

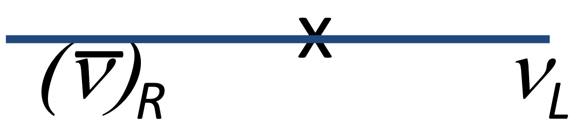



However, we are authorised to add a new mass term **only for neutrinos**

## 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:

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

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 in order to put the Lagrangian in the form:

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

# See-saw mechanism

$\mathbf{m_D}$ must be of the same order of the charged lepton masses (Higgs mechanism)

$\mathbf{M_R}$ can be everywhere (GUT scale)
→ the condition $\mathbf{M_R >> m_D}$ can naturally explain the small neutrino masses

**Eigenvalues**

$$m_1 \sim m_D^2 / M_R$$

$$m_2 \sim M_R + m_D^2 / M_R$$

**Light Majorana neutrinos** ⇒ **Those that undergo flavor oscillations**

**Eigenvectors**

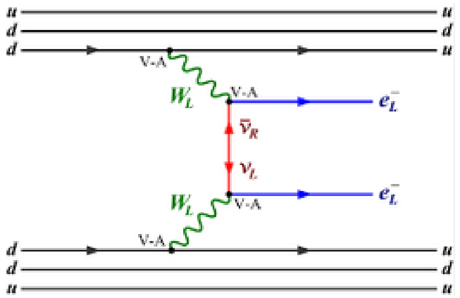
$$\nu_1 \sim \nu_L + \nu_L^c - (m_D / M_R)(\nu_R + \nu_R^c)$$

$$\nu_2 \sim \nu_R + \nu_R^c + (m_D / M_R)(\nu_L + \nu_L^c)$$

**Heavy Majorana neutrinos**, usually indicated with **N** → **Leptogenesis**

# Standard mechanism for 0ν2β

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




neutrinoless Double Beta Decay **rate**

Phase space

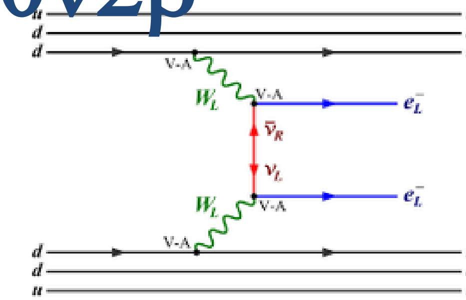
Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

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

# Standard mechanism for 0ν2β




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

Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

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

Experiments

Calculable

Controversial

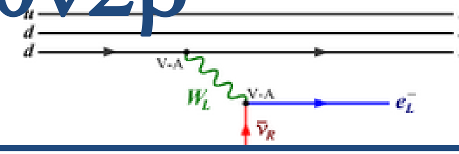
**J. Menendez**

Nuclear theory

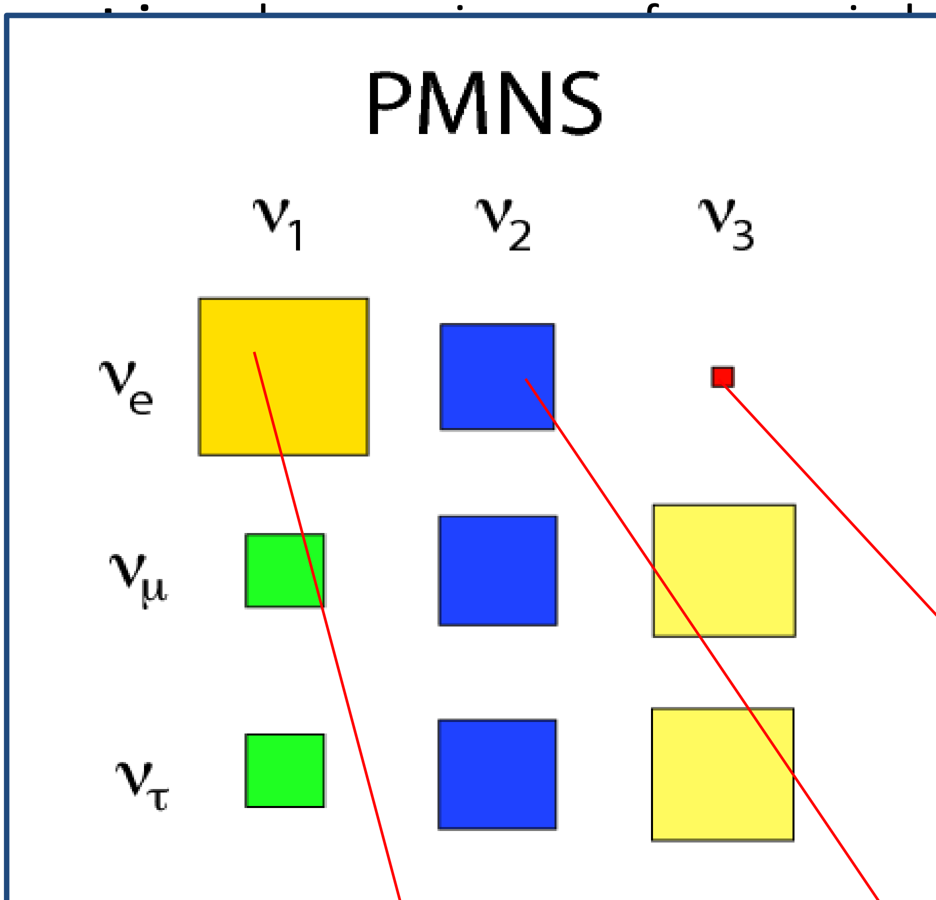
Neutrino physcis

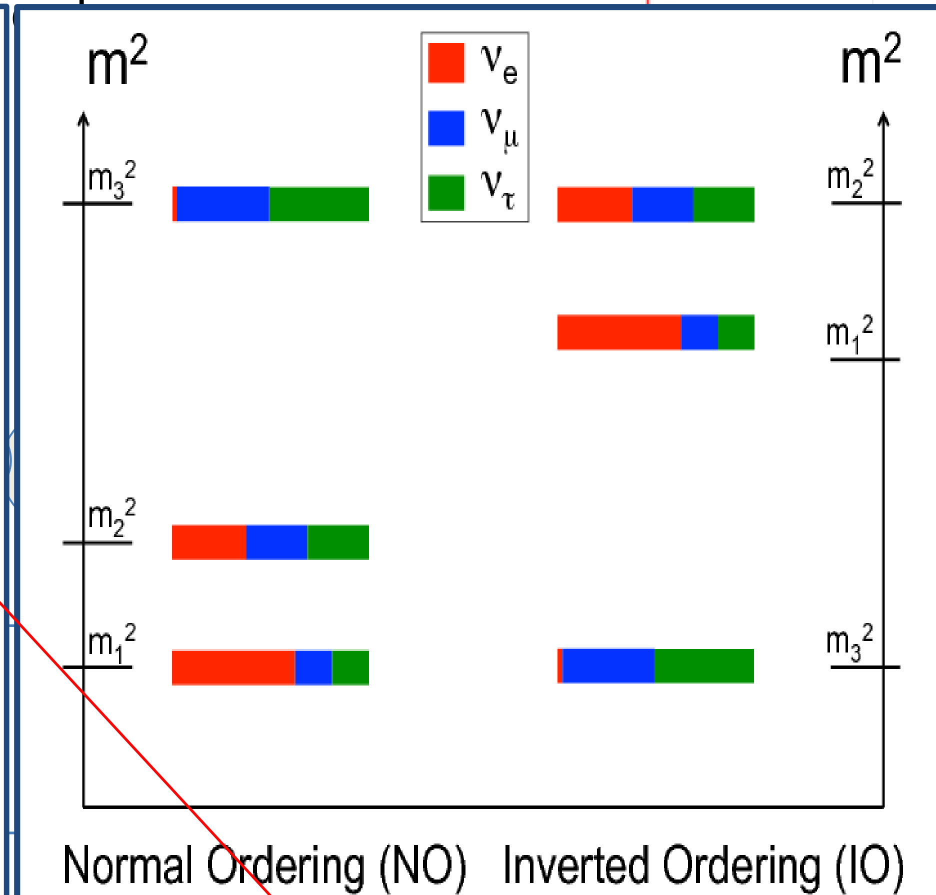
$$\mathbf{m_{ee}} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

# Standard mechanism for 0ν2β



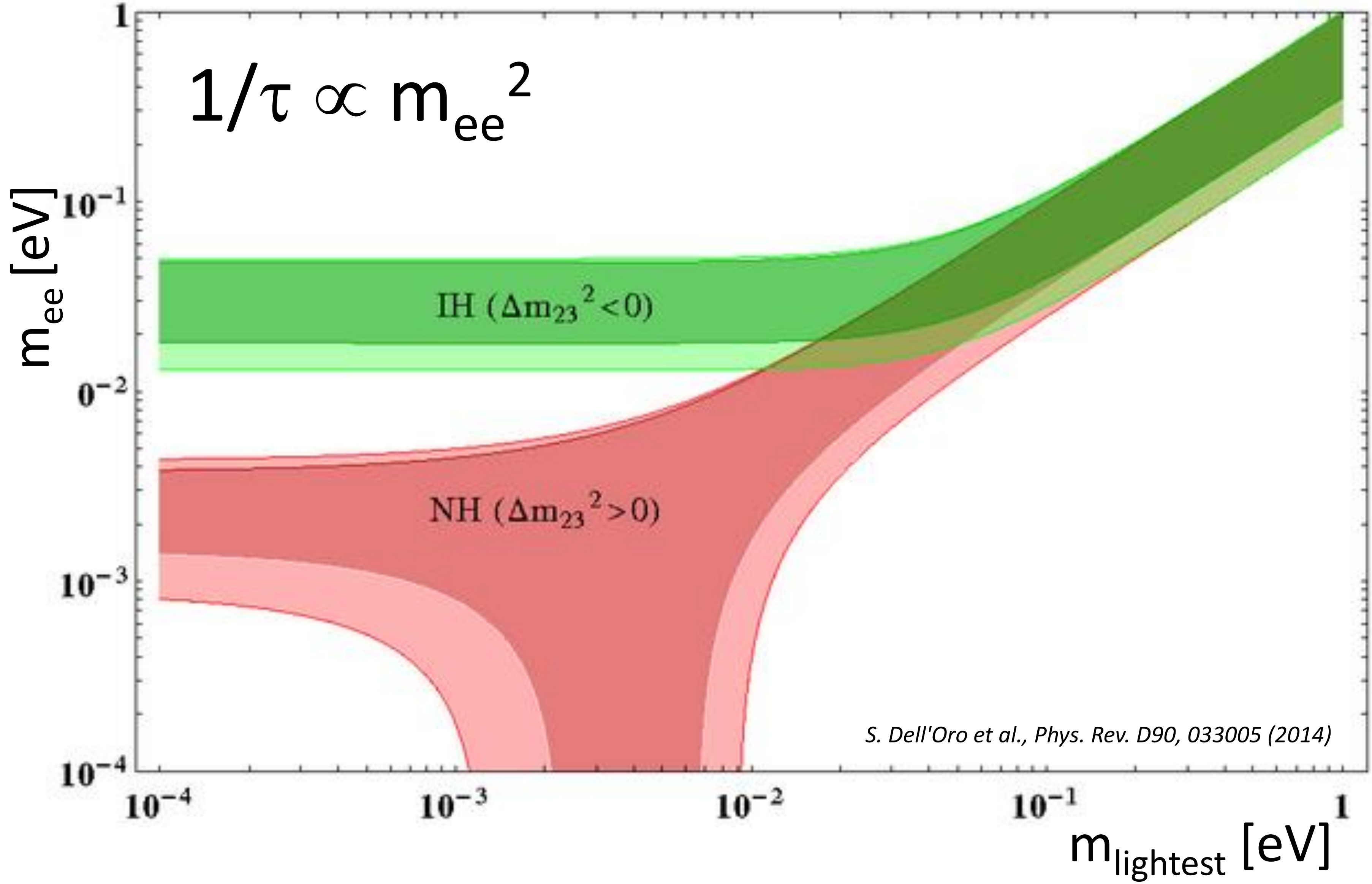
How **0ν-DBD** is connected to **neutrino mixing**



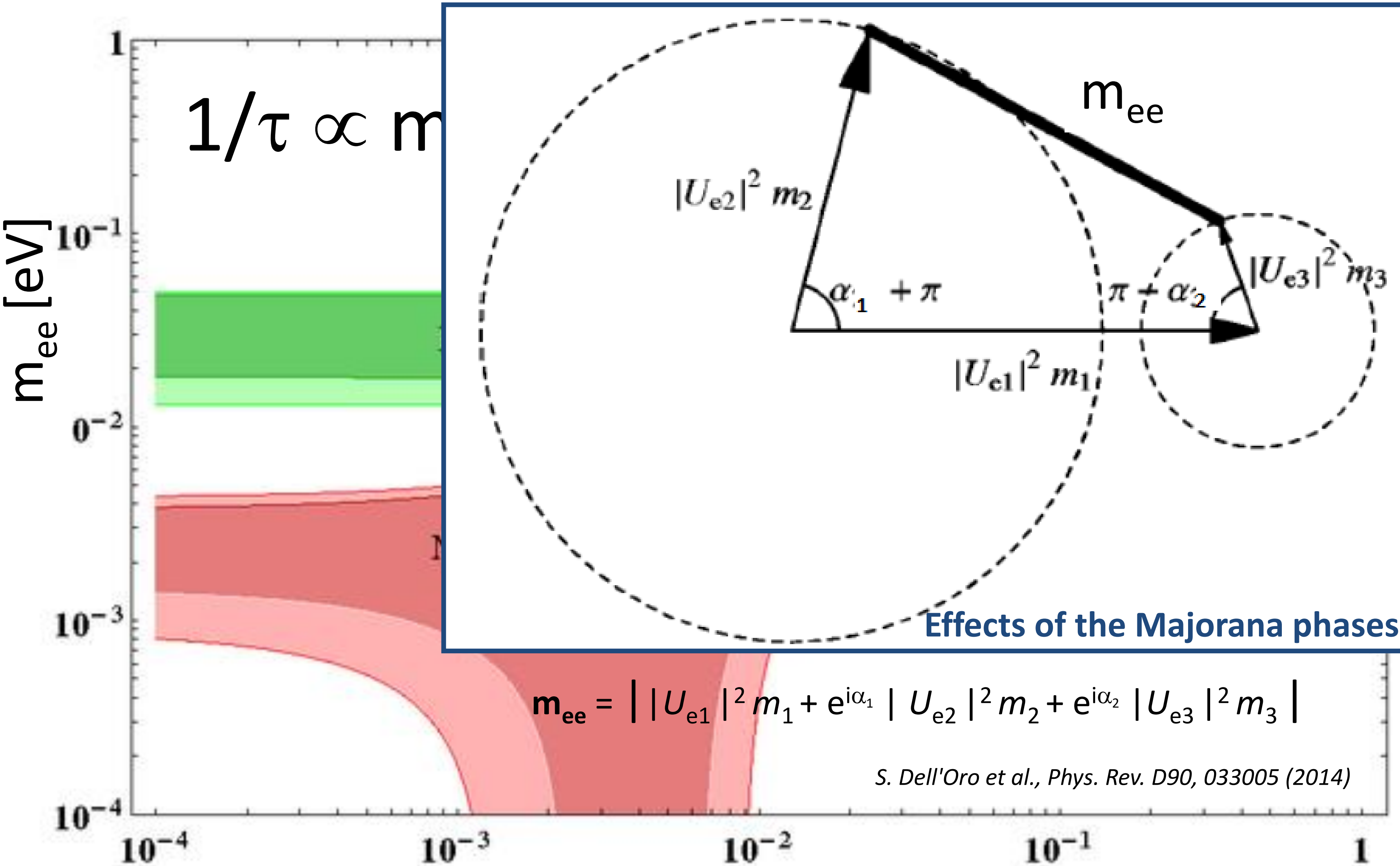




$$\mathbf{m_{ee}} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

# $m_{ee}$ vs. lightest $\nu$ mass



# $m_{ee}$ vs. lightest ν mass




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

*S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)*

# Challenges

**$g_A$ quenching**

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

$g_A$ =
- 1.269 — Free nucleon
- 1.25 — Often taken in the calculations
- 1 — Quark

J. Barea et al. and Ejiri et al. realized that **$g_A$ is quenched** in $2\nu2\beta$ decay (as in all $\beta$-like processes)

$g_{A,eff}$ **~ 0.6 – 0.8** (depending on model)

**Sever reduction of the rate**

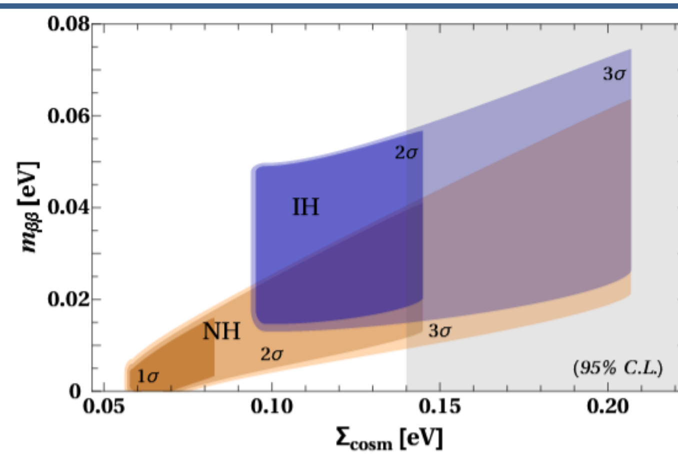
However, **it is not clear if observed quenching can be generalised to $0\nu2\beta$**

Constraints from cosmology on $\Sigma = \mathbf{m_1 + m_2 + m_3}$

Upper limits ranging in the interval **~ 0.2 – 0.6 eV** depending on the model and data-sets used for the analysis

**R. Battye**

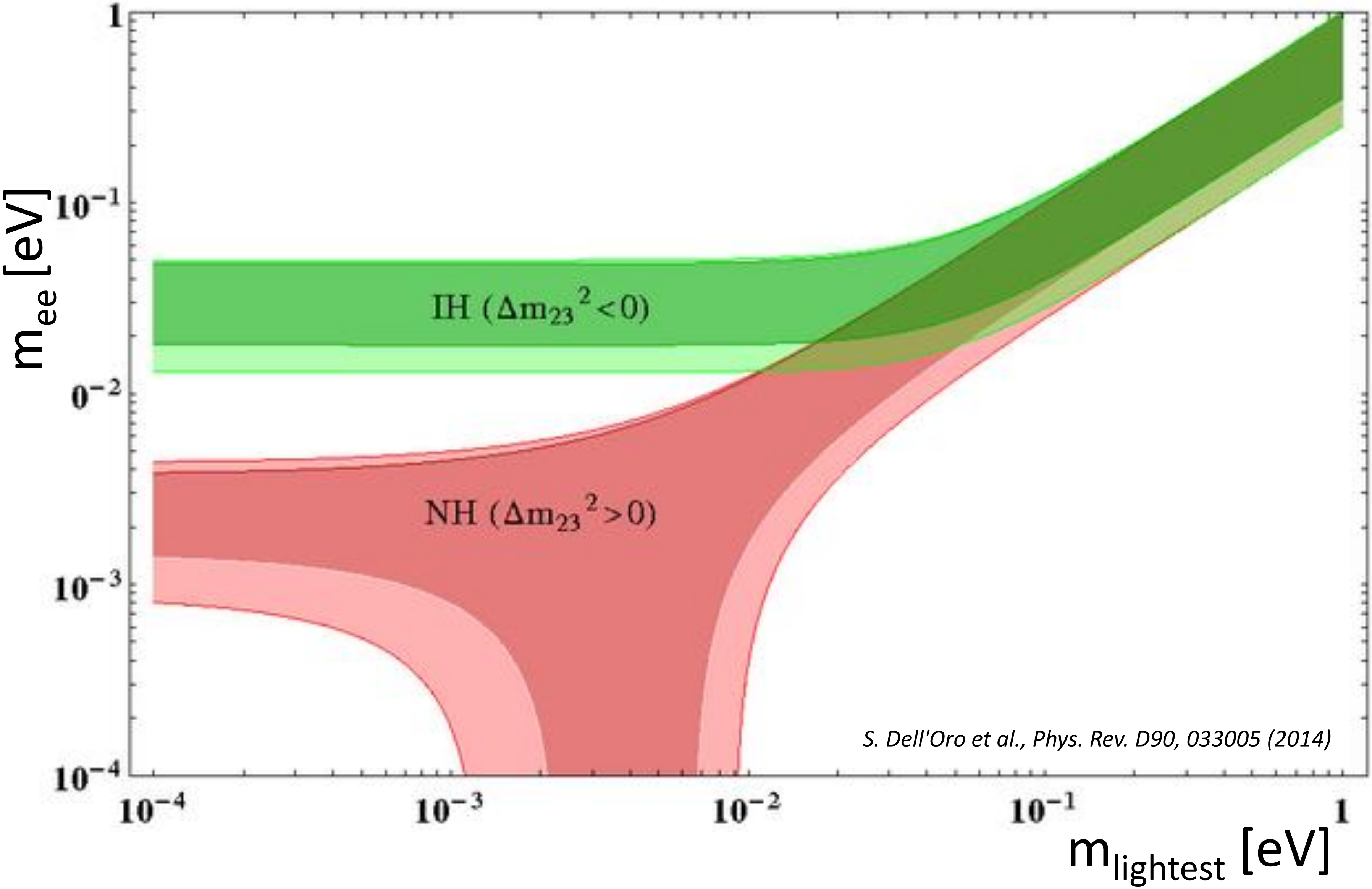
**Model-dependent constraint**



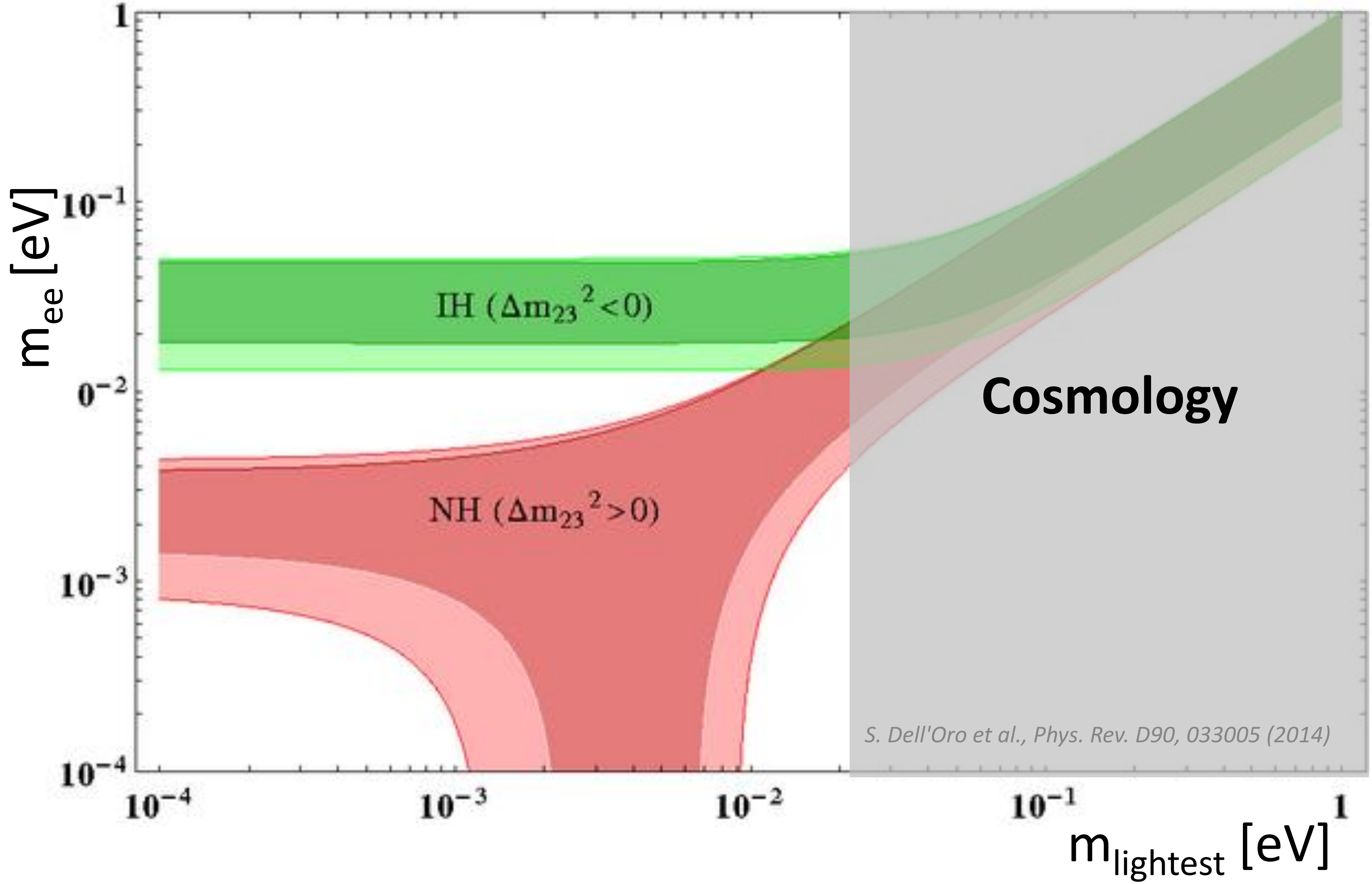

Indication in favor of **Normal Ordering**

Neutrino oscillation in terrestrial matter
Results from **NOvA**, **T2K**, **MINOS**
**Global analysis**

# Challenges


1
$10^{-1}$
$0^{-2}$
$10^{-3}$
$10^{-4}$
$m_{ee}$ [eV]
IH ($\Delta m_{23}{}^2 < 0$)
NH ($\Delta m_{23}{}^2 > 0$)
S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
$m_{lightest}$ [eV]

# Challenges


1
$10^{-1}$
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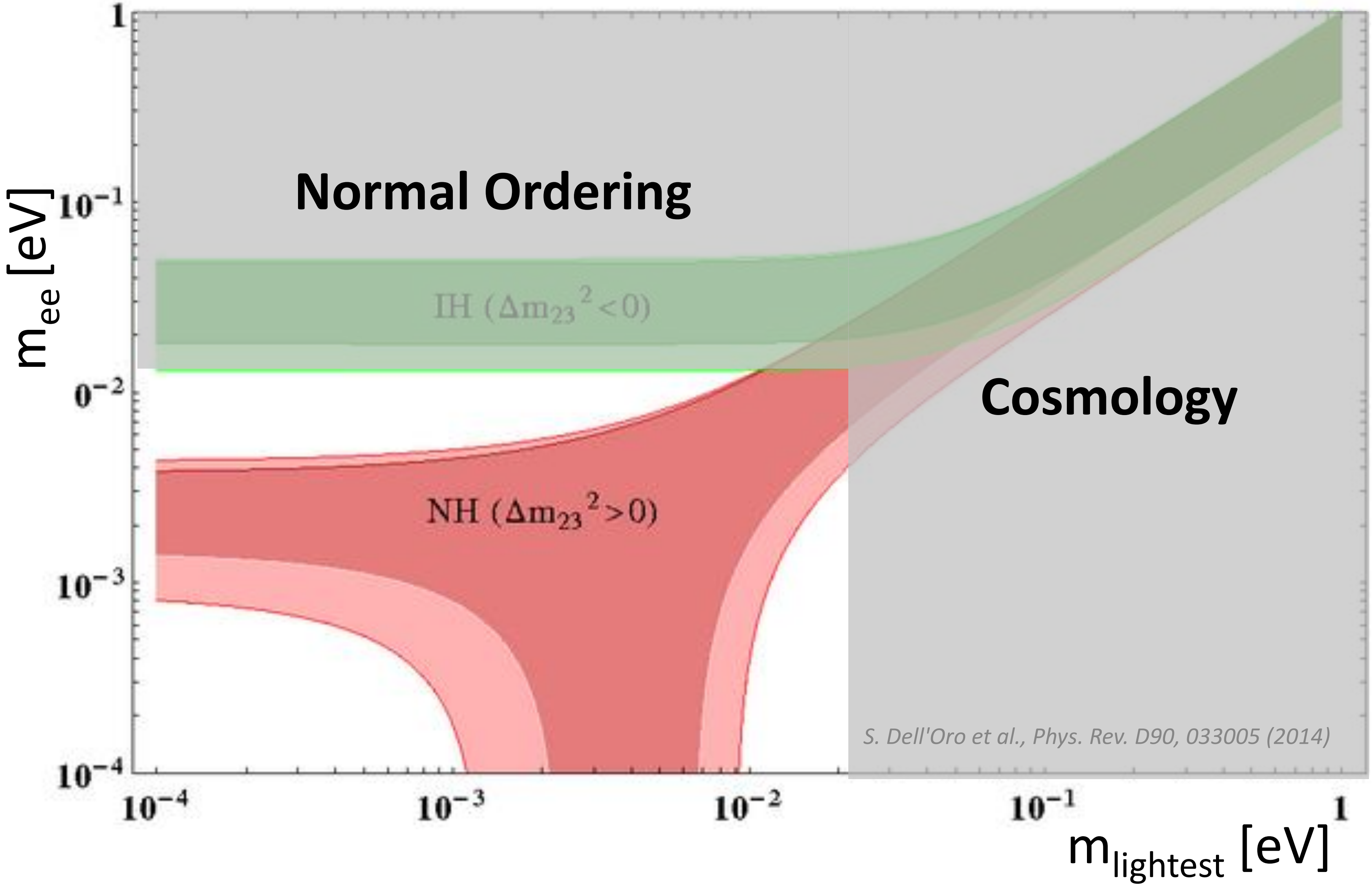
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
$m_{lightest}$ [eV]

# Challenges


Normal Ordering
IH ($\Delta m_{23}{}^2 < 0$)
NH ($\Delta m_{23}{}^2 > 0$)
Cosmology
S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)
$m_{ee}$ [eV]
$m_{lightest}$ [eV]
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1

# $m_{\beta\beta}$ distribution in the parameter space

*Phys. Rev. D 96, 053001 (2017)* (see also *Phys. Rev. D 96, 073001 (2017)*)

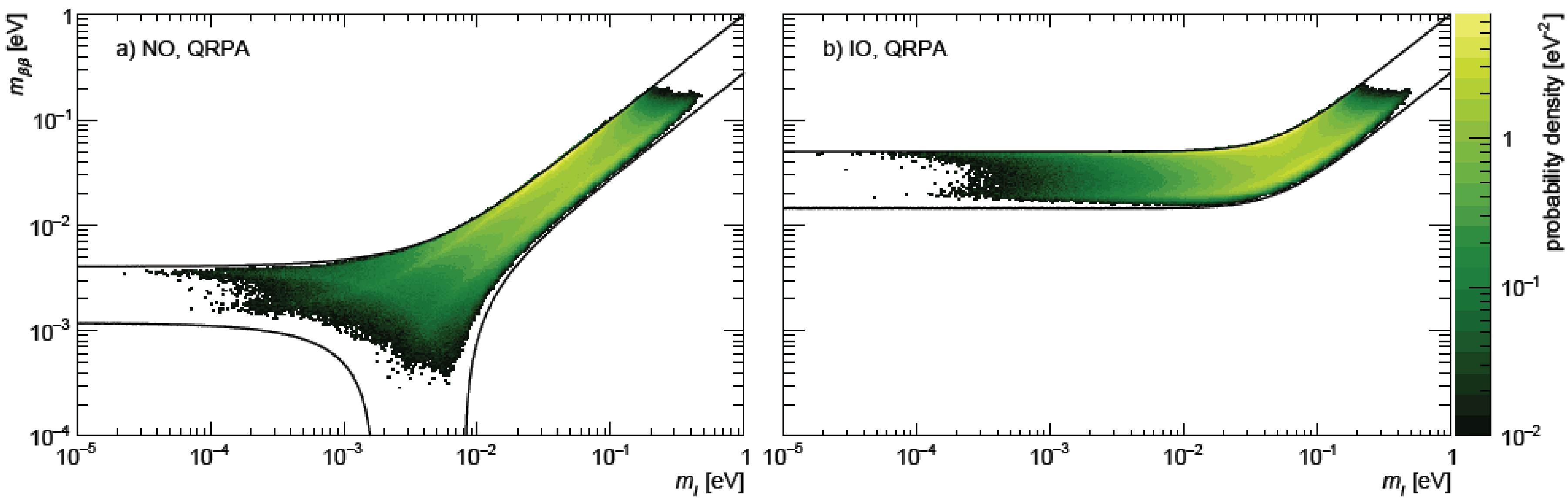
*Discovery probability of next-generation neutrinoless double-β decay experiments*

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

Ignorance of the scale of the parameters → **Scale-invariant prior distributions**

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

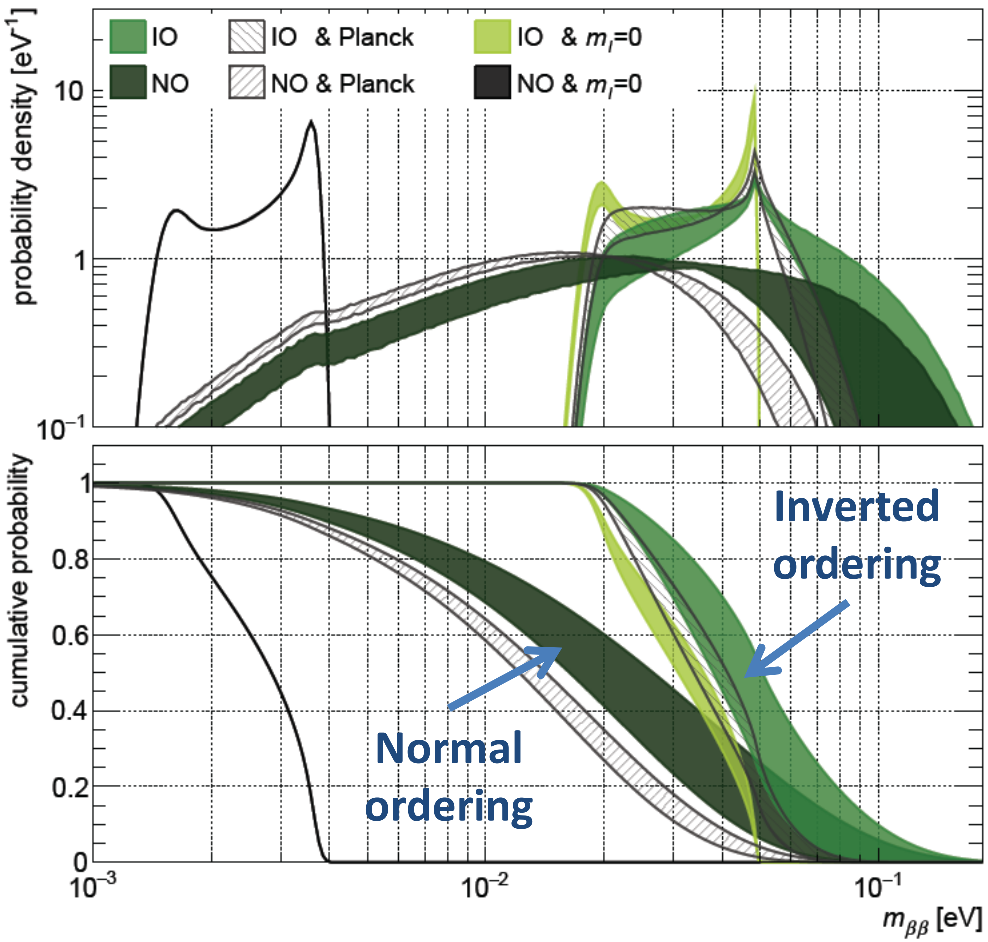
**Marginalized posterior distributions of $m_{\beta\beta}$**



# $m_{\beta\beta}$ distribution in the parameter space

*Phys. Rev. D 96, 053001 (2017)*

**Probability densities and cumulative probabilities for $m_{\beta\beta}$**




Next-generation most promising experiments have a **high discovery potential**:
The **cumulative probability** for $m_{\beta\beta}$ to be higher than **20 meV** is

- **1** for Inverted Ordering
- **~ 0.5** for Normal Ordering

**Cosmology** has a relatively small impact on this scenario.

**$g_A$ quenching** has an important effect but not dramatic

**30% $g_A$ quenching** reduces the discover potential by

- **~ 15%** for Inverted Ordering
- **~ 25%** for Normal Ordering

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- Double beta decay: what it is and why it is important
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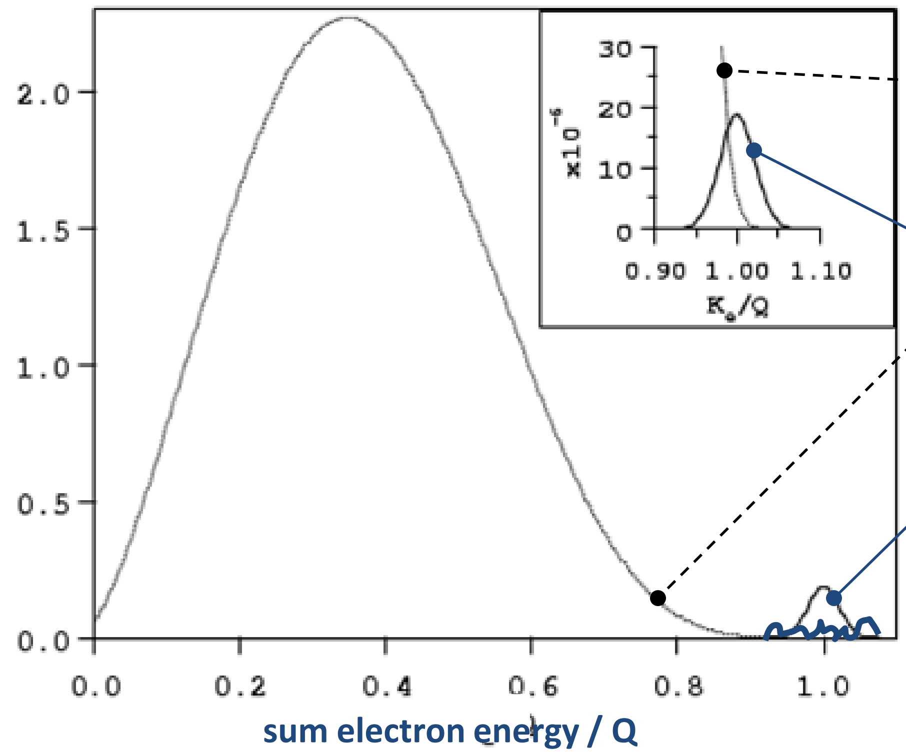
# What we are looking for

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




2ν2β : **(A,Z)→(A,Z+2)+2e+2ν**
continuum with maximum at ~1/3 Q

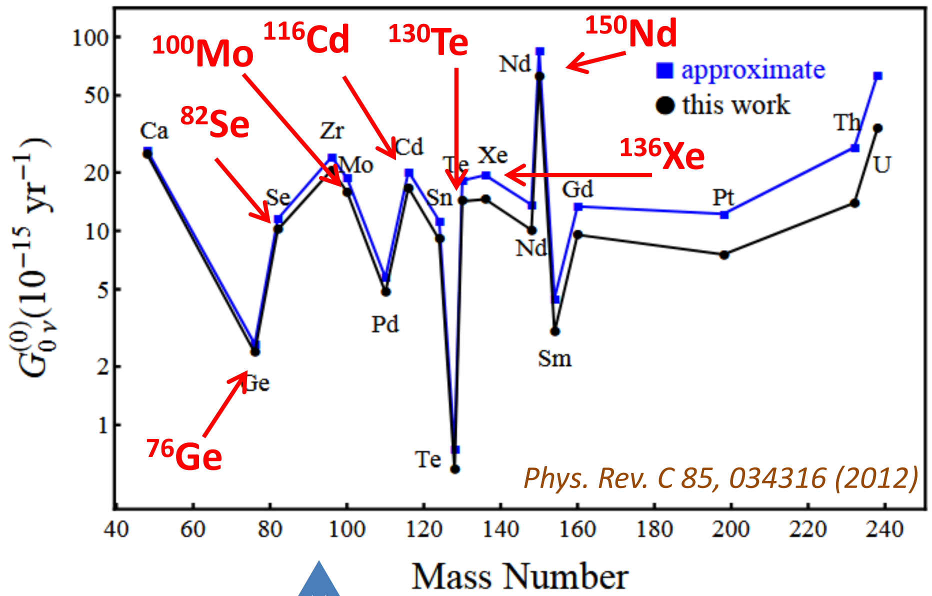
**0ν2β : (A,Z)→(A,Z+2)+2e**
peak enlarged only by
the detector energy resolution

**Q ~ 2-3 MeV** for the most promising candidates

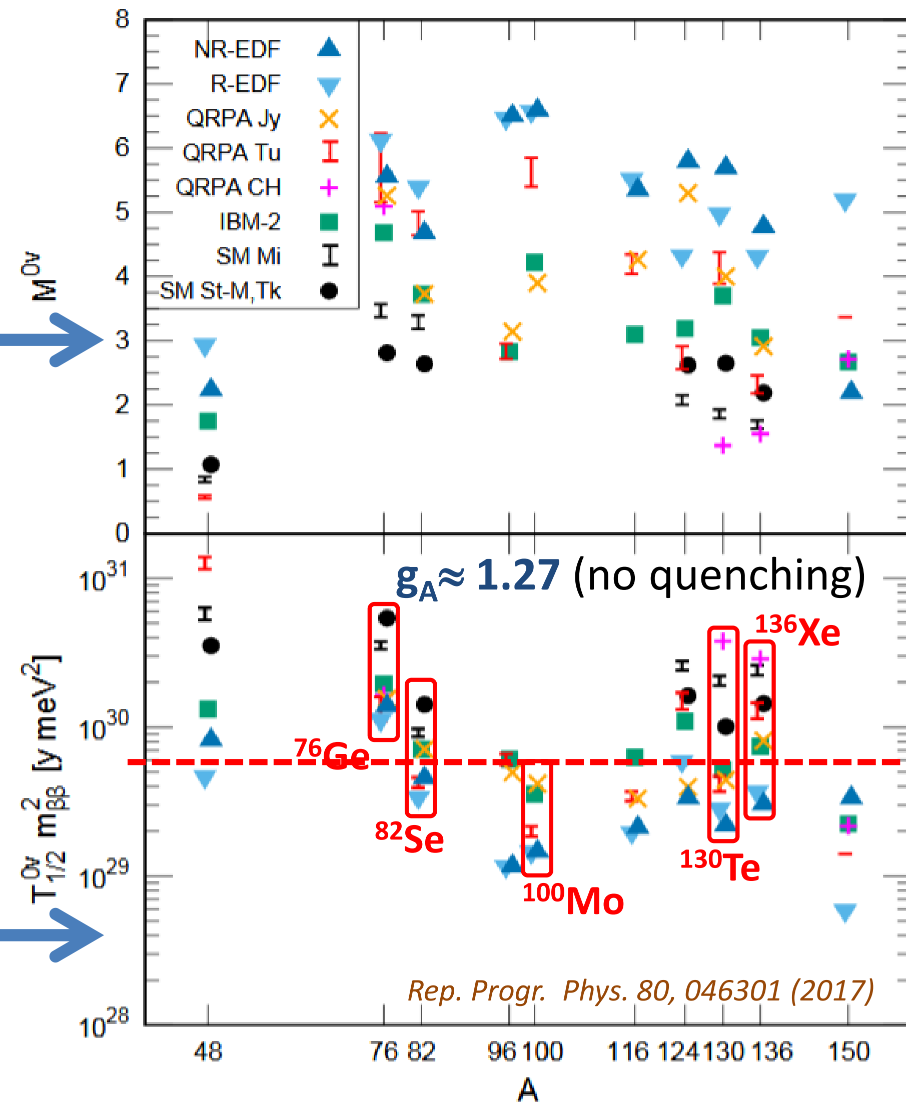
The signal is a **peak (at the Q-value)** over an almost **flat background**

# How difficult is it ?

**Phase space**: exactly calculable

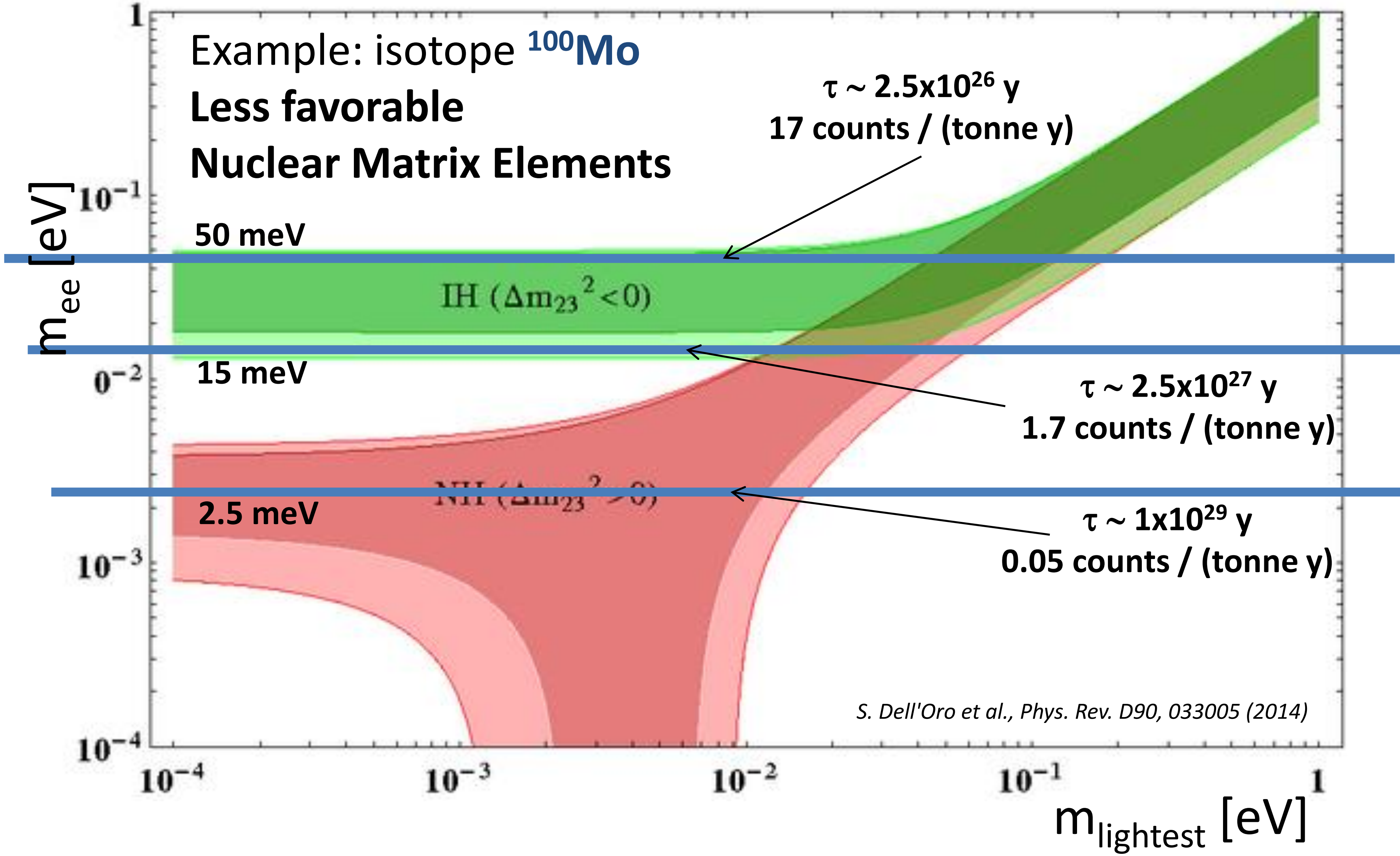



**Nuclear matrix elements**: several models

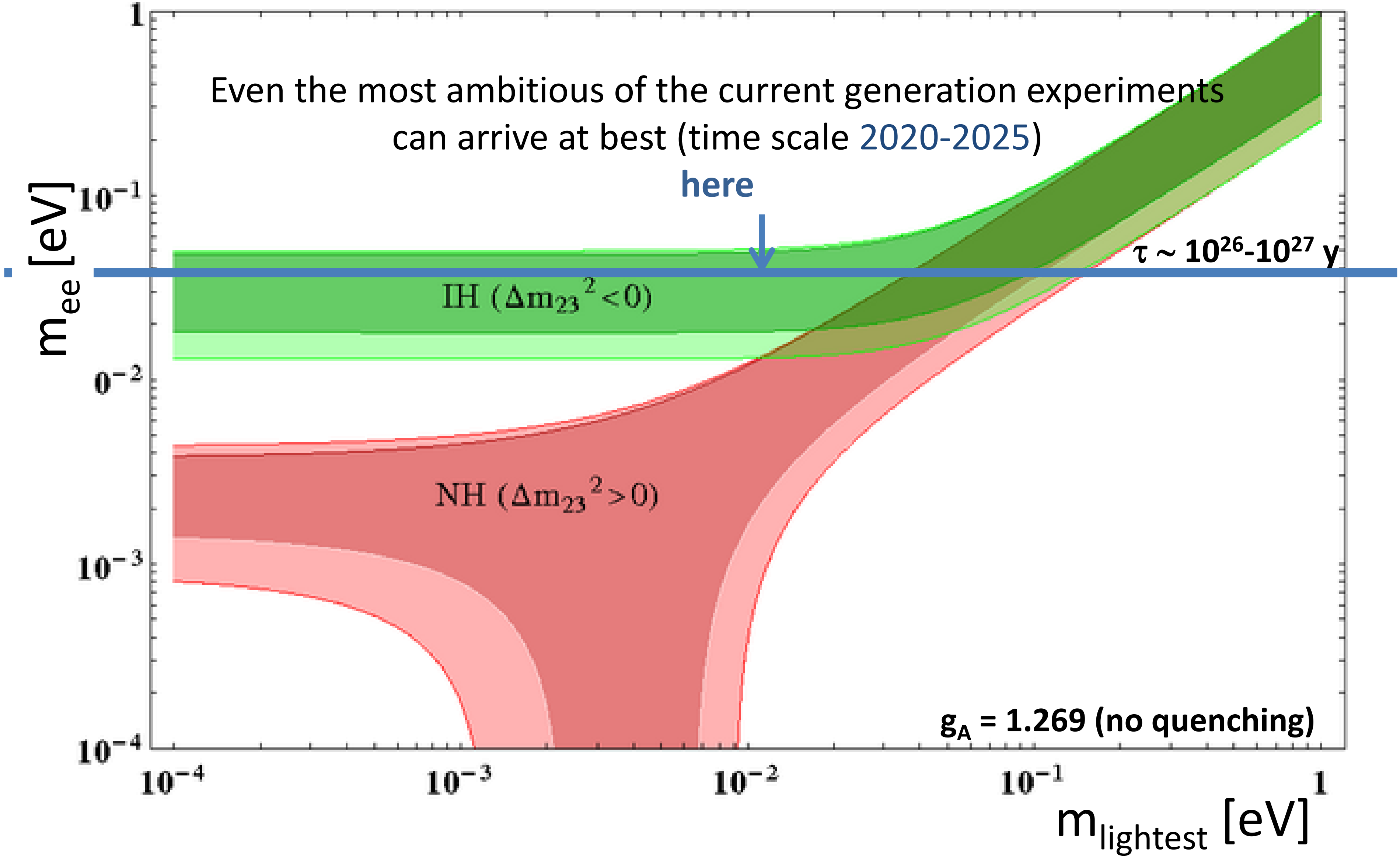



$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\,2}$$

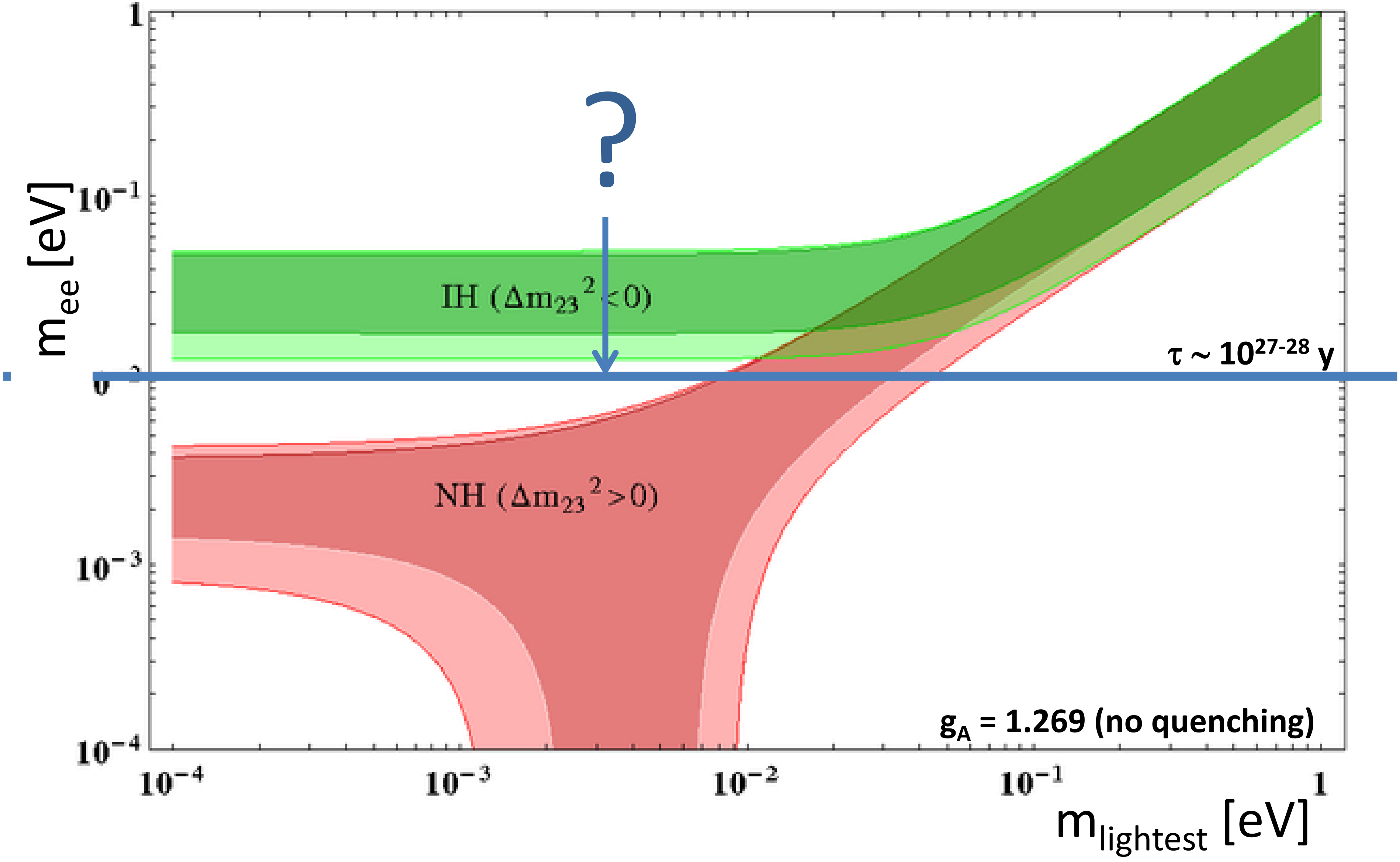
# How difficult is it ?



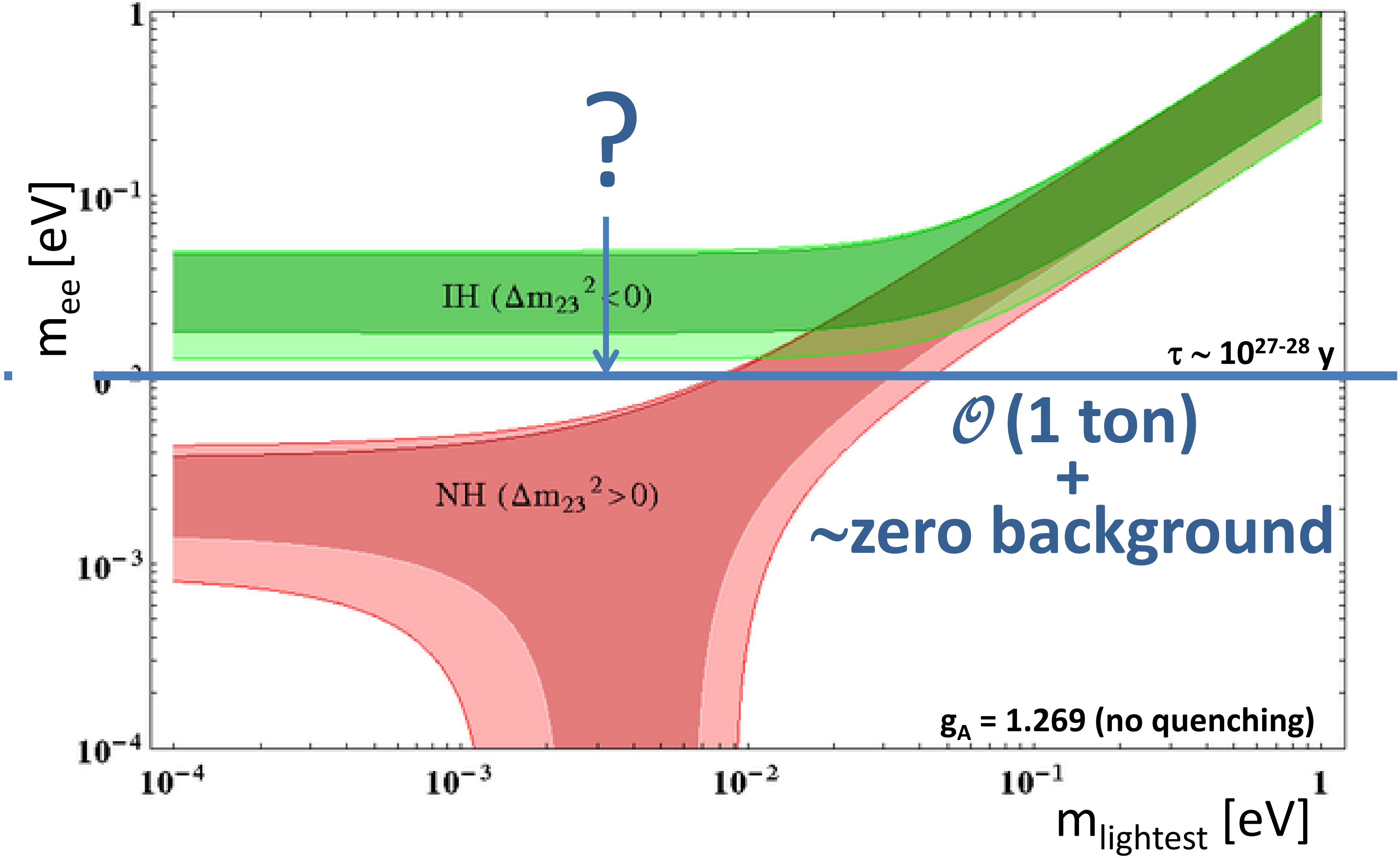
# Current-generation experiments



# Strategic milestone



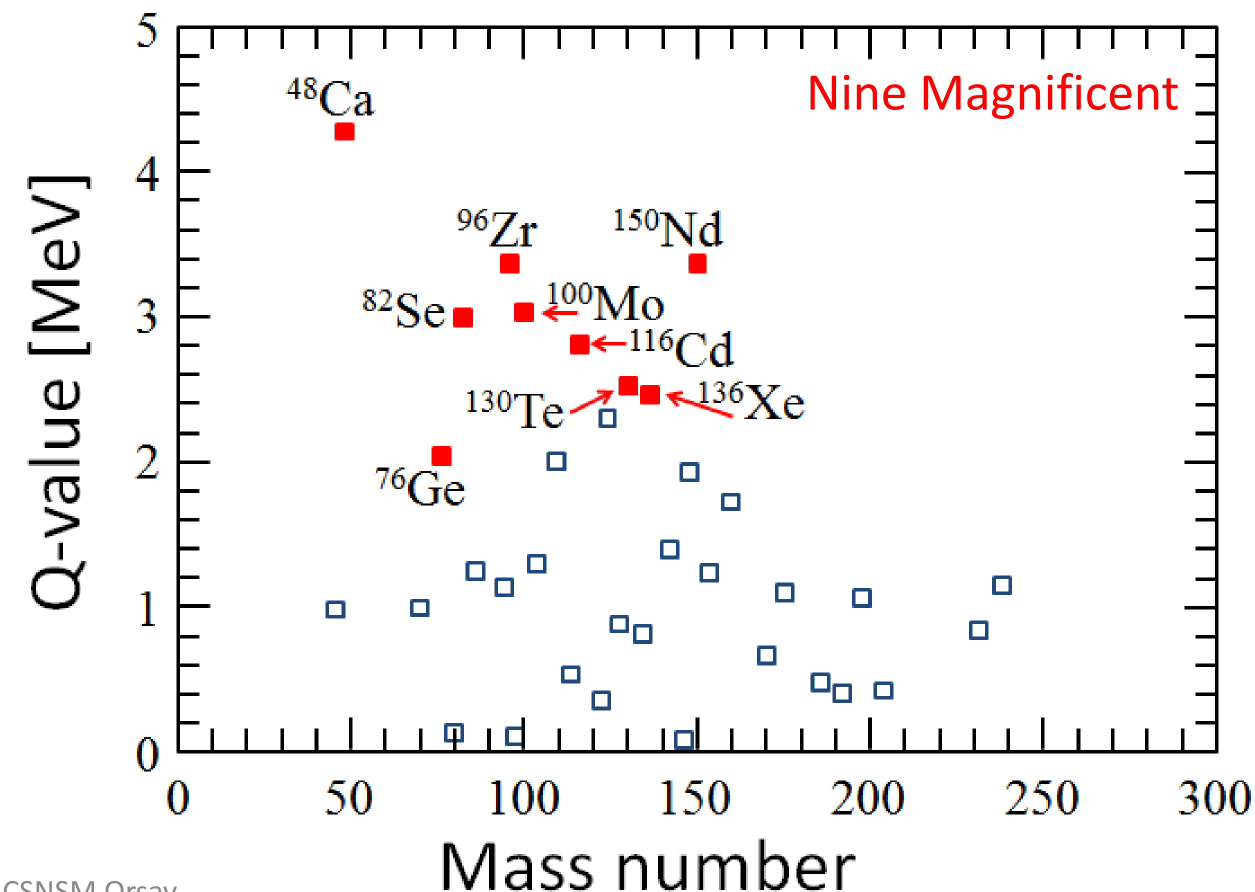
# Strategic milestone



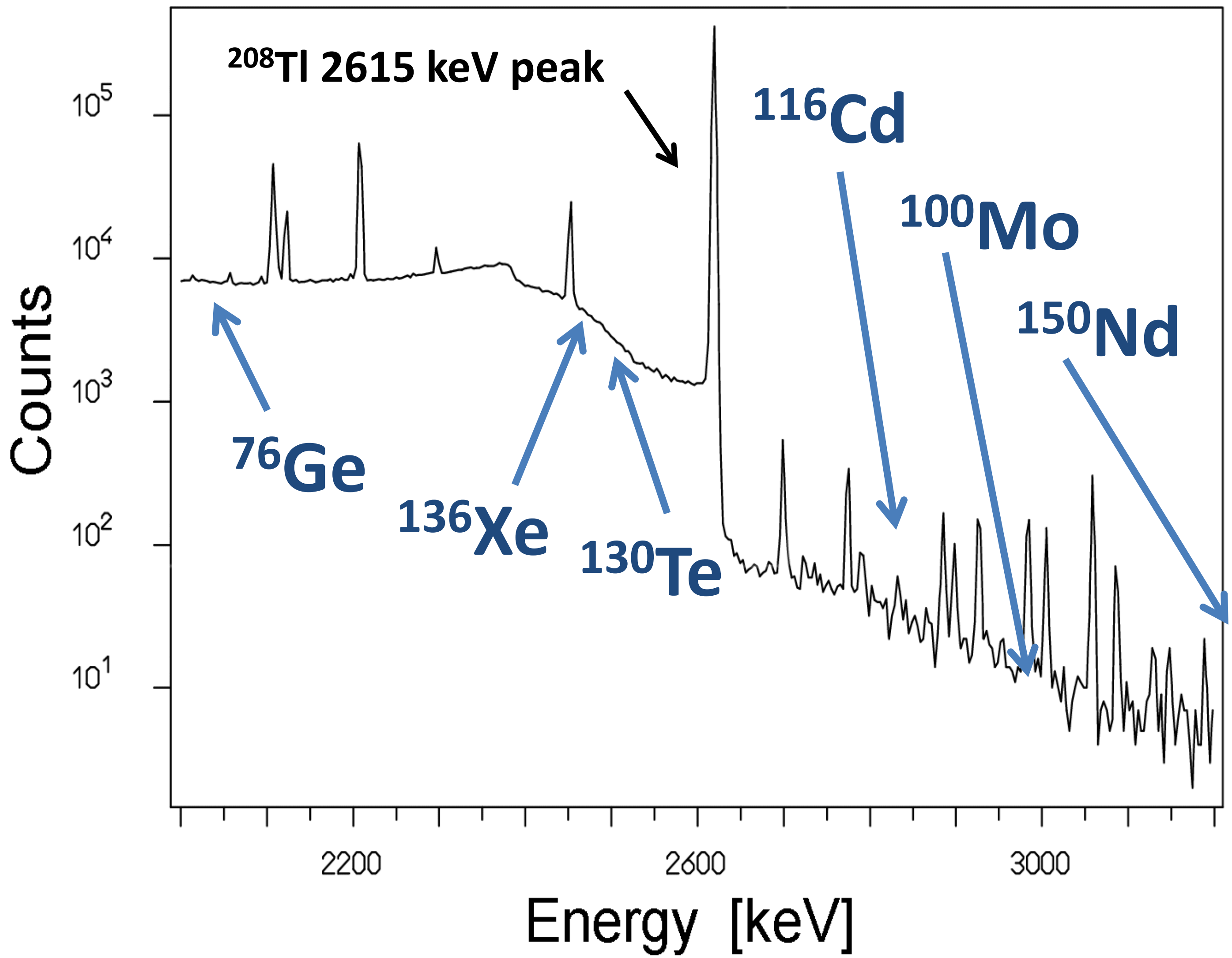
# Factors guiding isotope selection

**Q** is the crucial factor

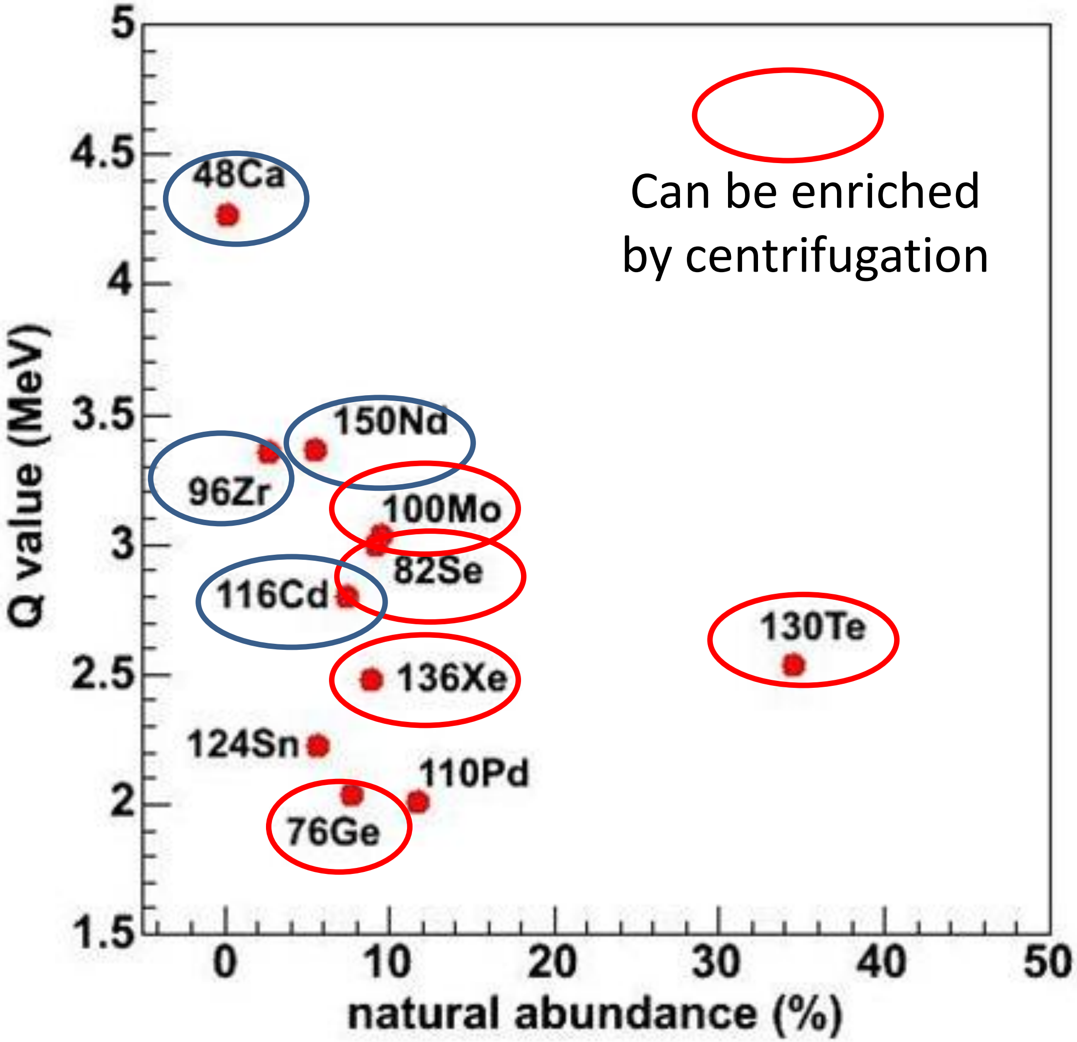
- Phase space: G(Q,Z) leading terme $\propto Q^5$
- Background

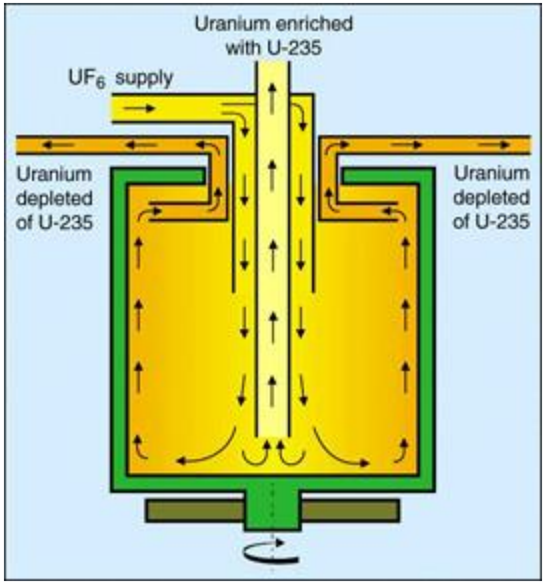


# Q-value and γ background



# Isotopic abundance




**Isotopic enrichment** by **centrifugation** – Currently, the only viable large-scale method

Almost, **Russian monopoly**

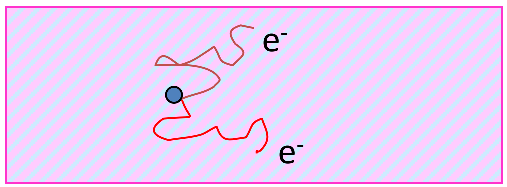
Cost: 10-80 €/g

**1 ton: 10 – 80 M€**

# How we do it: experimental approaches

Two approaches:

①




**Source ≡ Detector**
(calorimetric technique)

- solid-state devices
- bolometers
- gaseous/liquid detectors
- solid scintillators

→

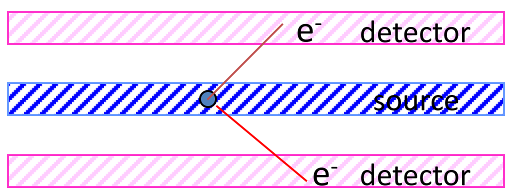
☹ constraints on detector materials

☺ very large masses are possible
demonstrated: up to ~ 0.1 - 1 ton

☺ with proper choice of the detector, very high energy resolution
- Ge-diodes
- bolometers

☺ in gaseous/liquid xenon detector, indication of event topology

②




**Source ≠ Detector**

- scintillation
- gaseous detectors
- magnetic field and TOF

→

☹ it is difficult to get large source mass

☺ neat reconstruction of event topology

☺ several candidates can be studied with the same detector

# The sensitivity

**sensitivity F**: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

Experiment with background

**b: specific background coefficient** [counts/(keV kg y)]

Zero background experiment

live time

source mass

energy resolution

**b ~ $10^{-4}$ or less**

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

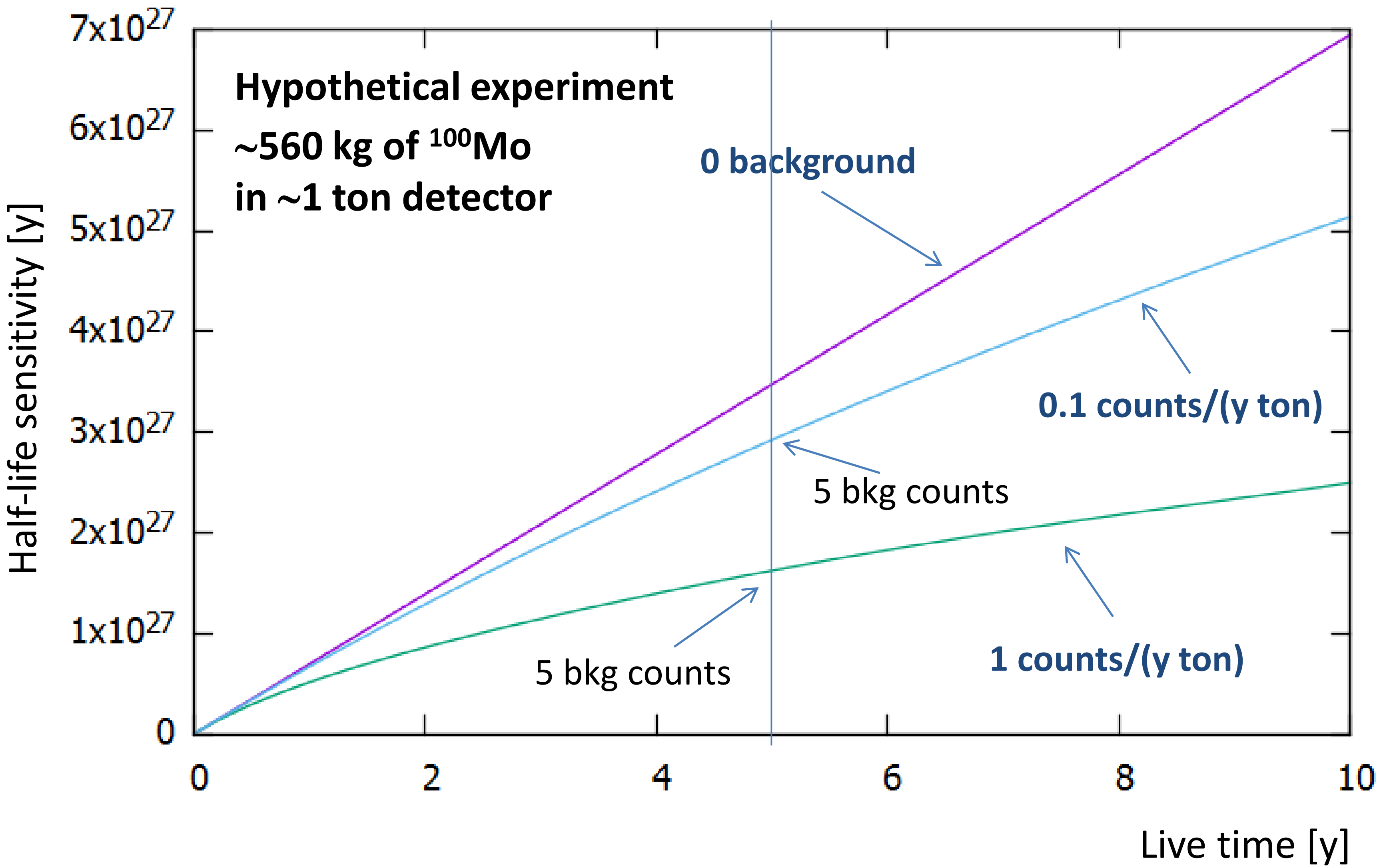
$$F \propto MT$$

nuclide choice
(large uncertainty due to nuclear physics)

$$\textbf{sensitivity to } m_{ee} \propto \frac{1}{Q^{1/2} \; |M_{nucl}|} \left( \frac{b\Delta E}{MT} \right)^{1/4}$$

If you reach a limit **M*** in 5 y, you have to measure **75 more years** to get **M*/2**

# Effect of the background on the sensitivity



# The struggle against environmental radioactivity

**Standard solutions**

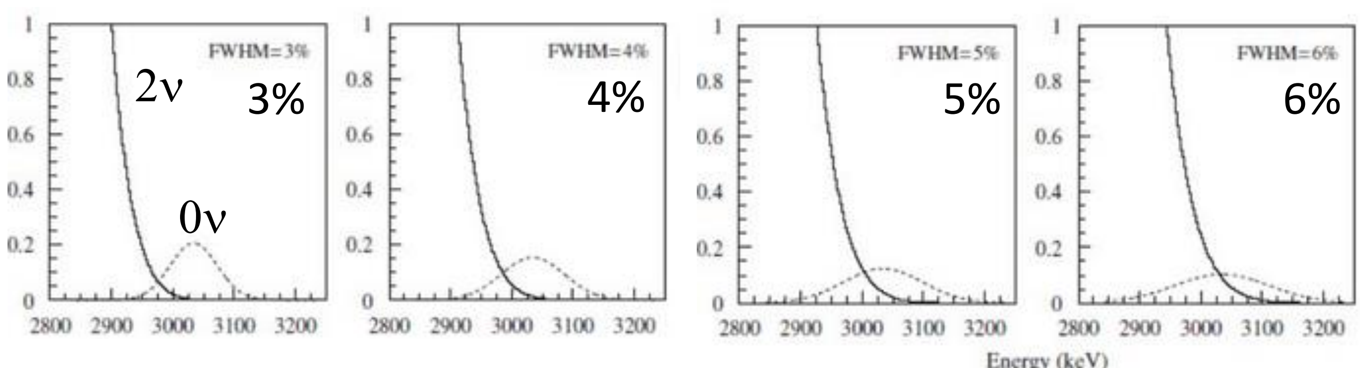
**Natural radioactivity (α, β, γ radiation)**
$T_{1/2}^{0\nu2\beta} > 10^{26}$ y ⟷ $T_{1/2}$ [$^{238}$U, $^{232}$Th, $^{40}$K] ~ $10^9$-$10^{10}$ y
➡ Levels of < 1 μBq / kg are required
Ordinary material ~ 1-100 Bq/kg

**Cosmic muons**
Above ground flux ~ 1 /(cm$^2$ × min)
➡ Underground laboratory
→ Flux reduction by > $10^6$

**Neutrons**
Generated by rock radioactivity and muons
➡ Quality and depth of the underground lab
Dedicated shielding are often required

**Cosmogenic induced activity (long living)**
Delayed effect of the cosmic radiation (activation)
➡ Choice of detector materials
Storage of material underground

**2 ν Double Beta Decay**
Spectrum leaking in the region of interest
➡ Energy and time resolution of detectors

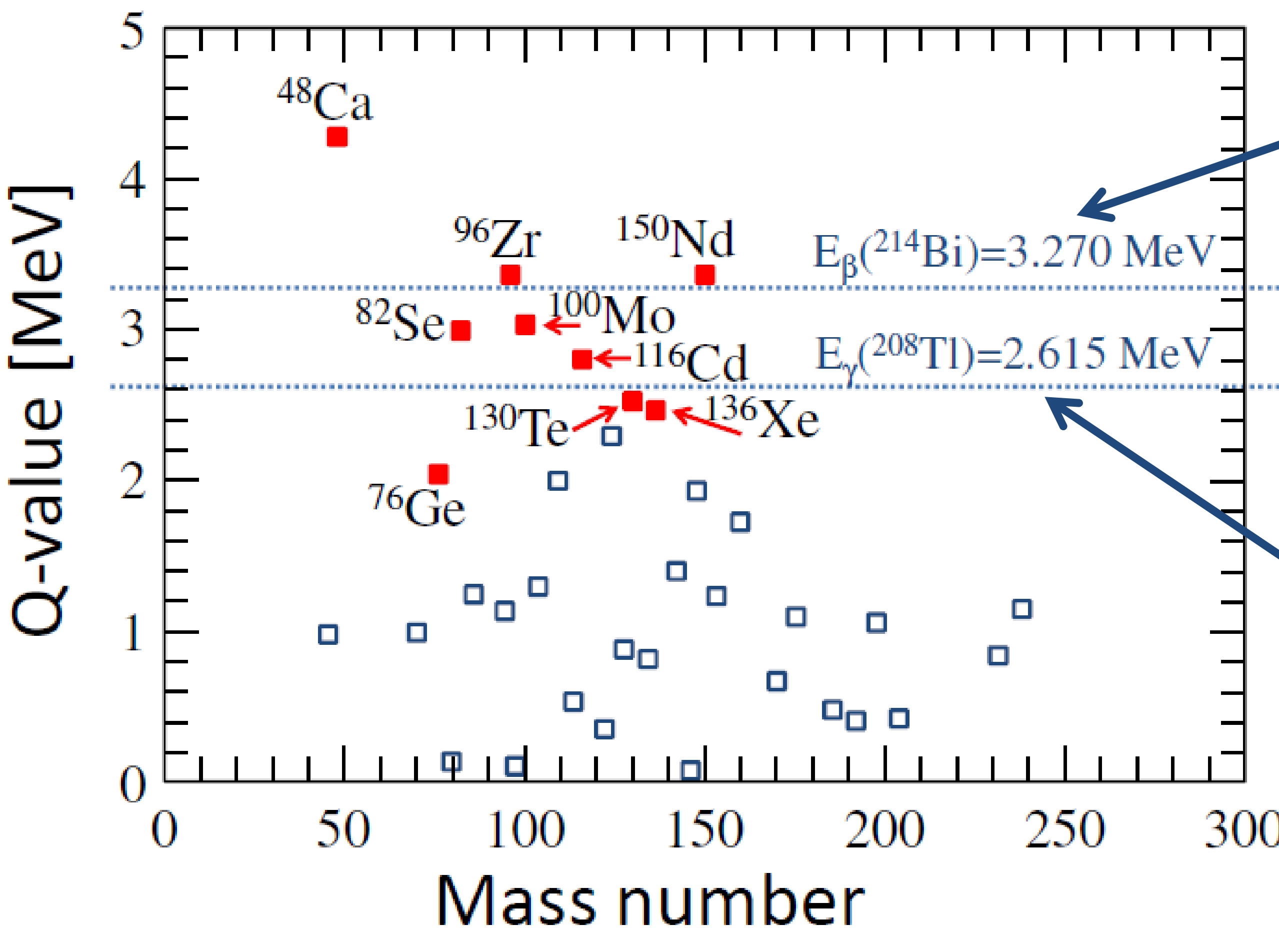



**$^{100}$ Mo**

**$T^{2\nu}_{1/2}$ ~ 7 x$10^{18}$ y**

**Fastest 2ν process**

# Isotope, enrichment and technique



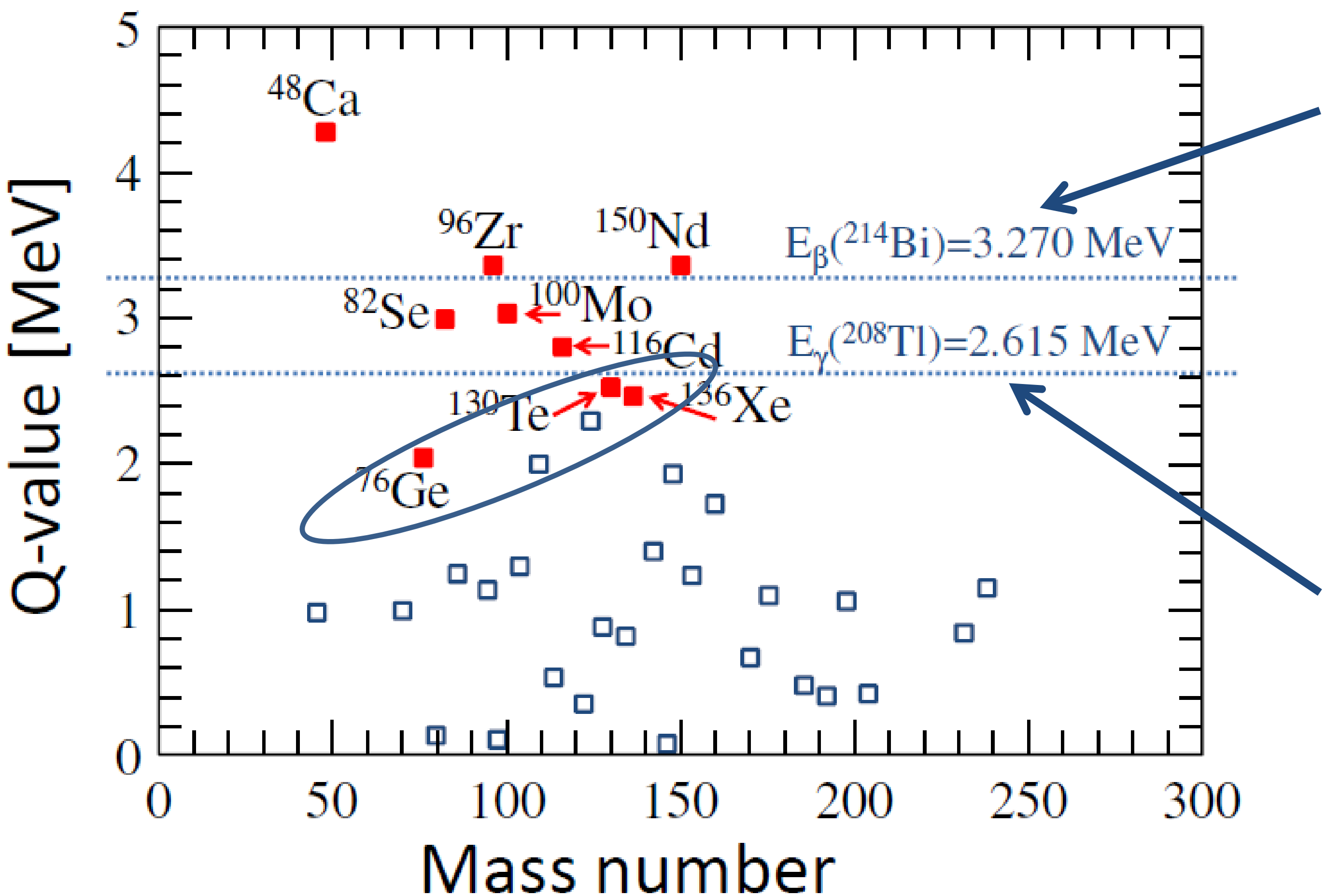

End-point of $^{222}$Rn-induced radioactivity

End-point of natural $\gamma$ radioactivity

# Outline

- Double beta decay: what it is and why it is important
- How we search for neutrinoless double beta decay
- Overview of the current experimental situation
- Details of the most important experiments
- Challenges for the future

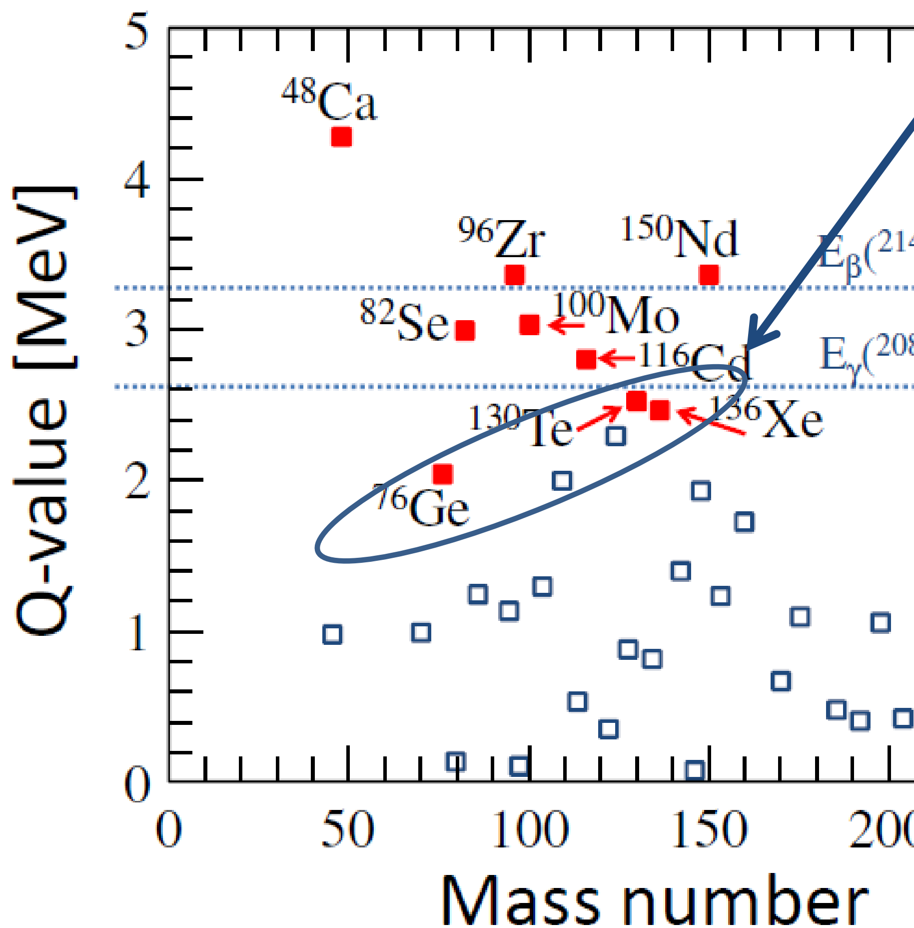
# Isotope, enrichment and technique




End-point of $^{222}$Rn-induced radioactivity

End-point of natural $\gamma$ radioactivity

# Isotope, enrichment and technique




Excellent technologies are available in the source=detector approach:

- **Ge diodes ⇒ $^{76}$Ge (GERDA, MAJORANA)** - ΔE<<1%
- **Bolometers ⇒ $^{130}$Te ($TeO_2$ crystals) (CUORE)** - ΔE<<1%
- **Dissolving the element** (**Te**) in a large liquid scintillator volume **(SNO+)**
- **TPCs (EXO, NEXT,PANDA-X-III), inclusion in large volume of liquid scintillator (KamLAND-Zen) ⇒ $^{136}$Xe**

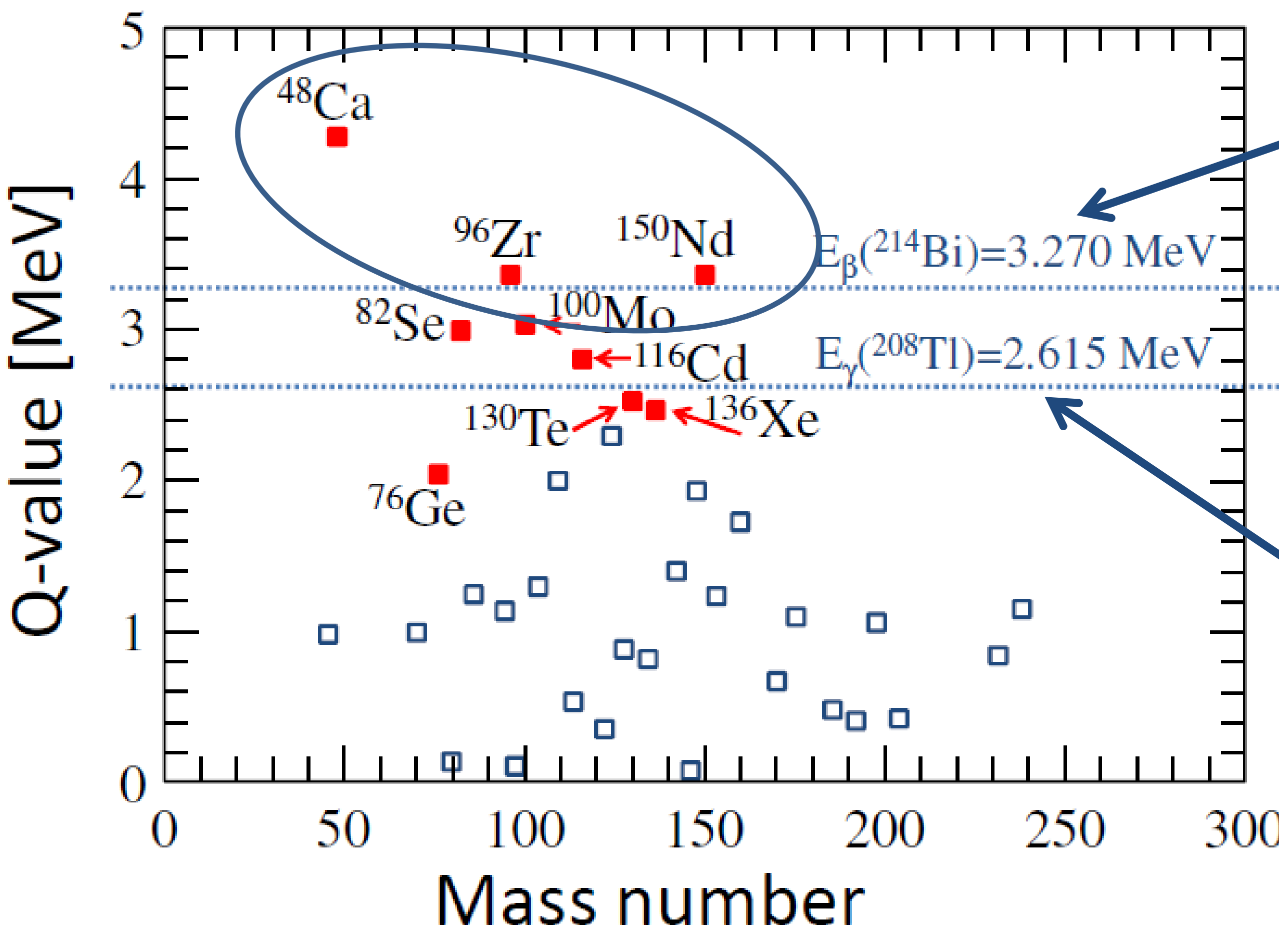
Enrichment is "easy" and for $^{130}$Te not necessary at the present level

**BUT**

Less favorable in terms of background!

In red, based on the bolometric technique

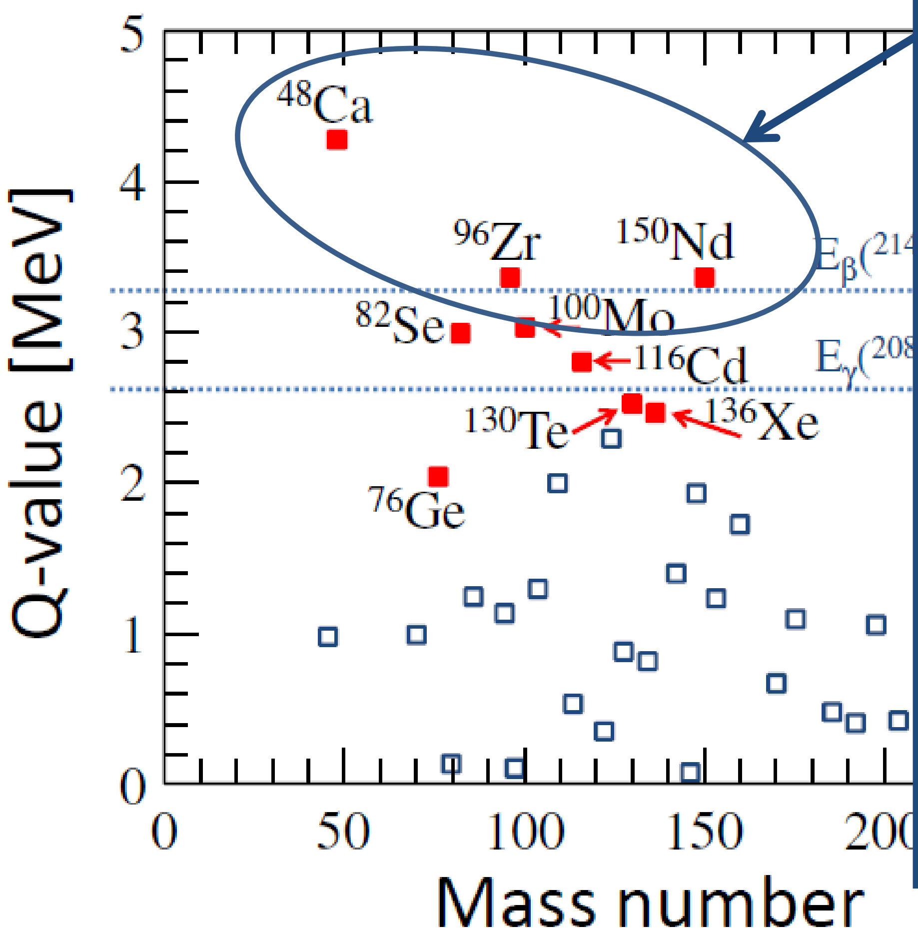
# Isotope, enrichment and technique




End-point of $^{222}$Rn-induced radioactivity

End-point of natural $\gamma$ radioactivity

# Isotope, enrichment and technique




Almost background free isotopes!

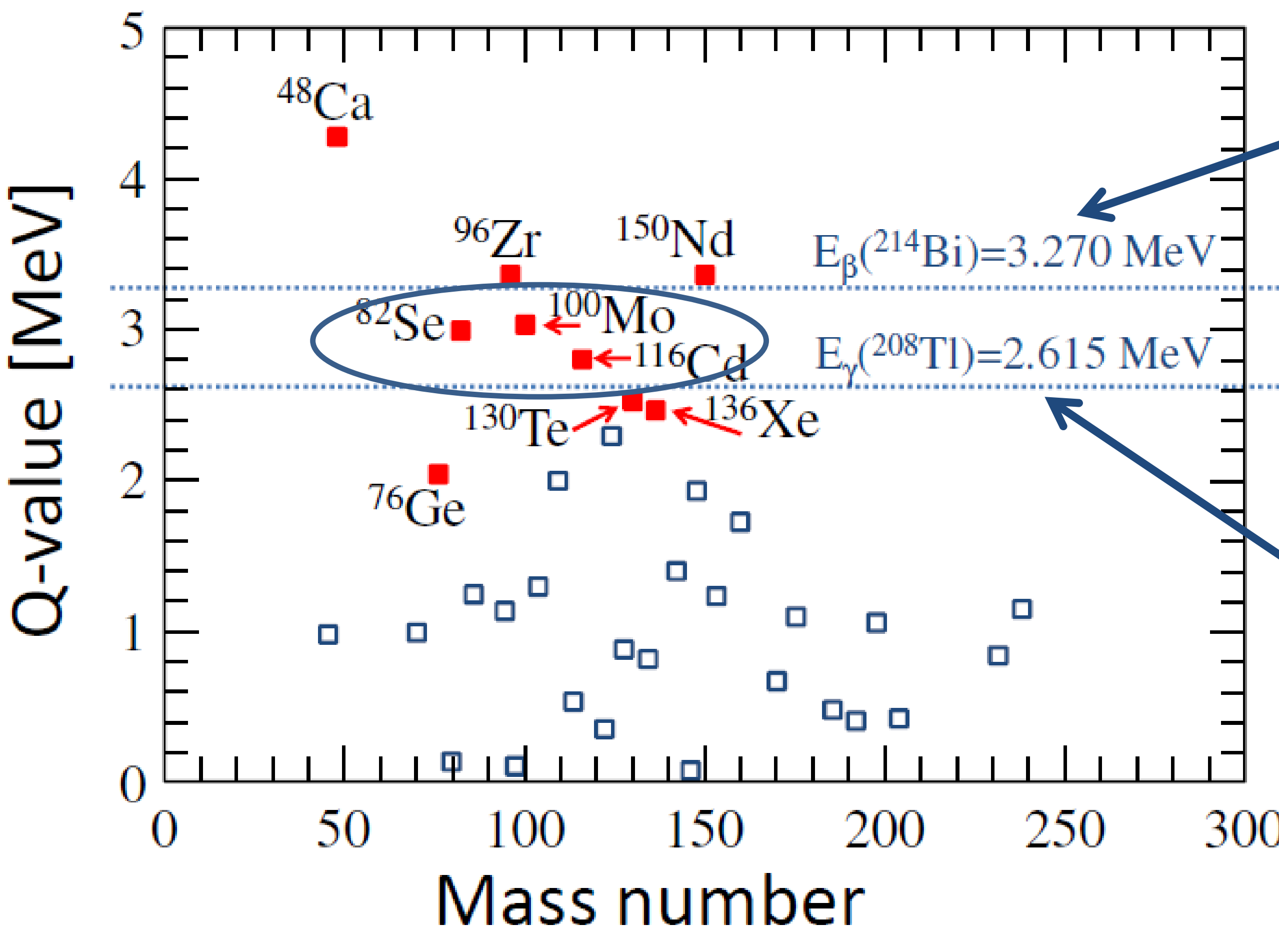
**BUT**

Low isotopic abundance and problematic enrichment (good news about Nd)

Better studied with source≠detector (**tracko-calo approach**) (**SuperNEMO**)

**$CaF_2$ scintillators** (and in principle bolometers) are interesting for **$^{48}Ca$** **(CANDLES)**

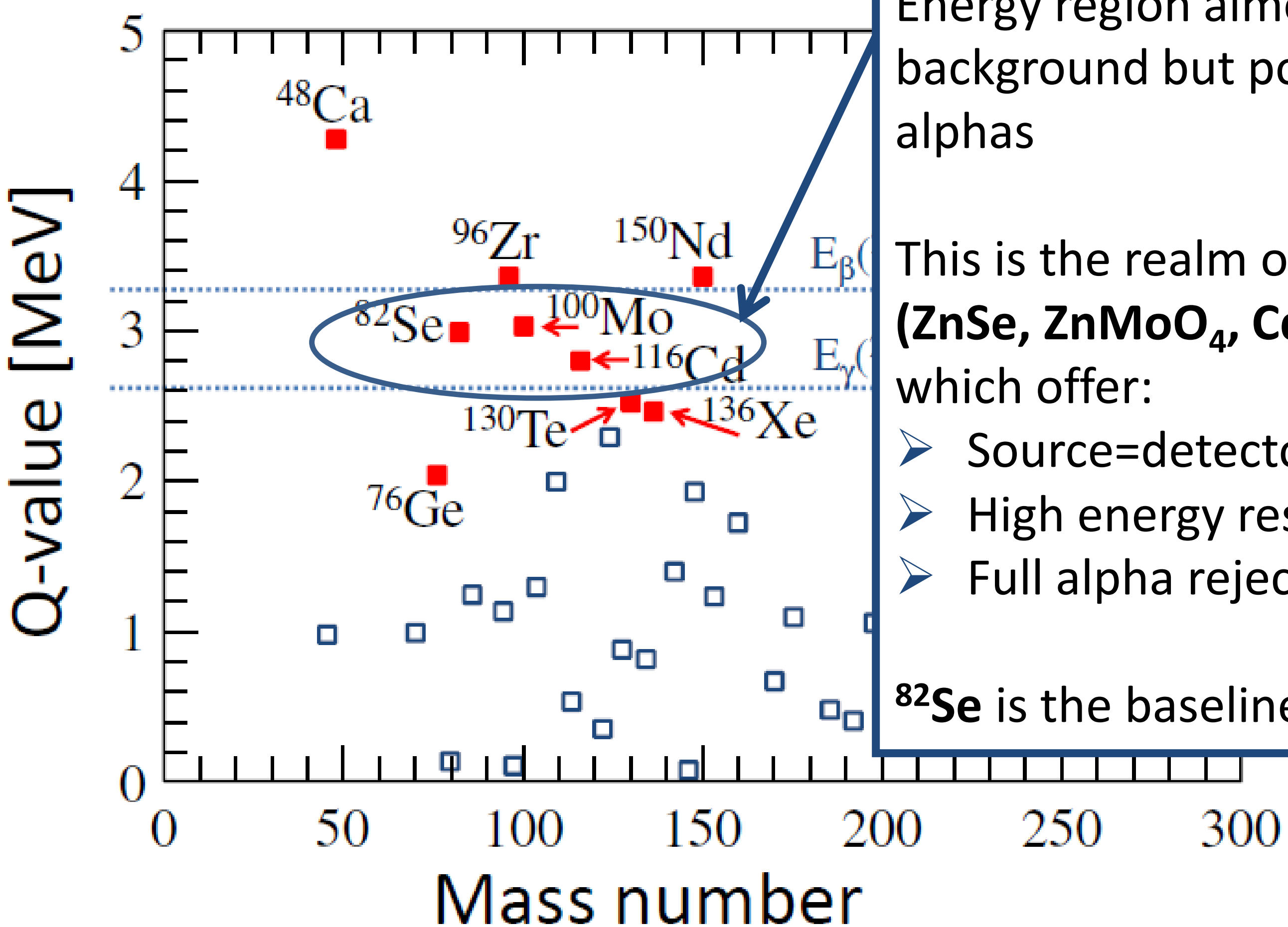
# Isotope, enrichment and technique




End-point of $^{222}$Rn-induced radioactivity

End-point of natural $\gamma$ radioactivity

# Isotope, enrichment and technique




Energy region almost free from natural $\gamma$ background but populated by degraded alphas

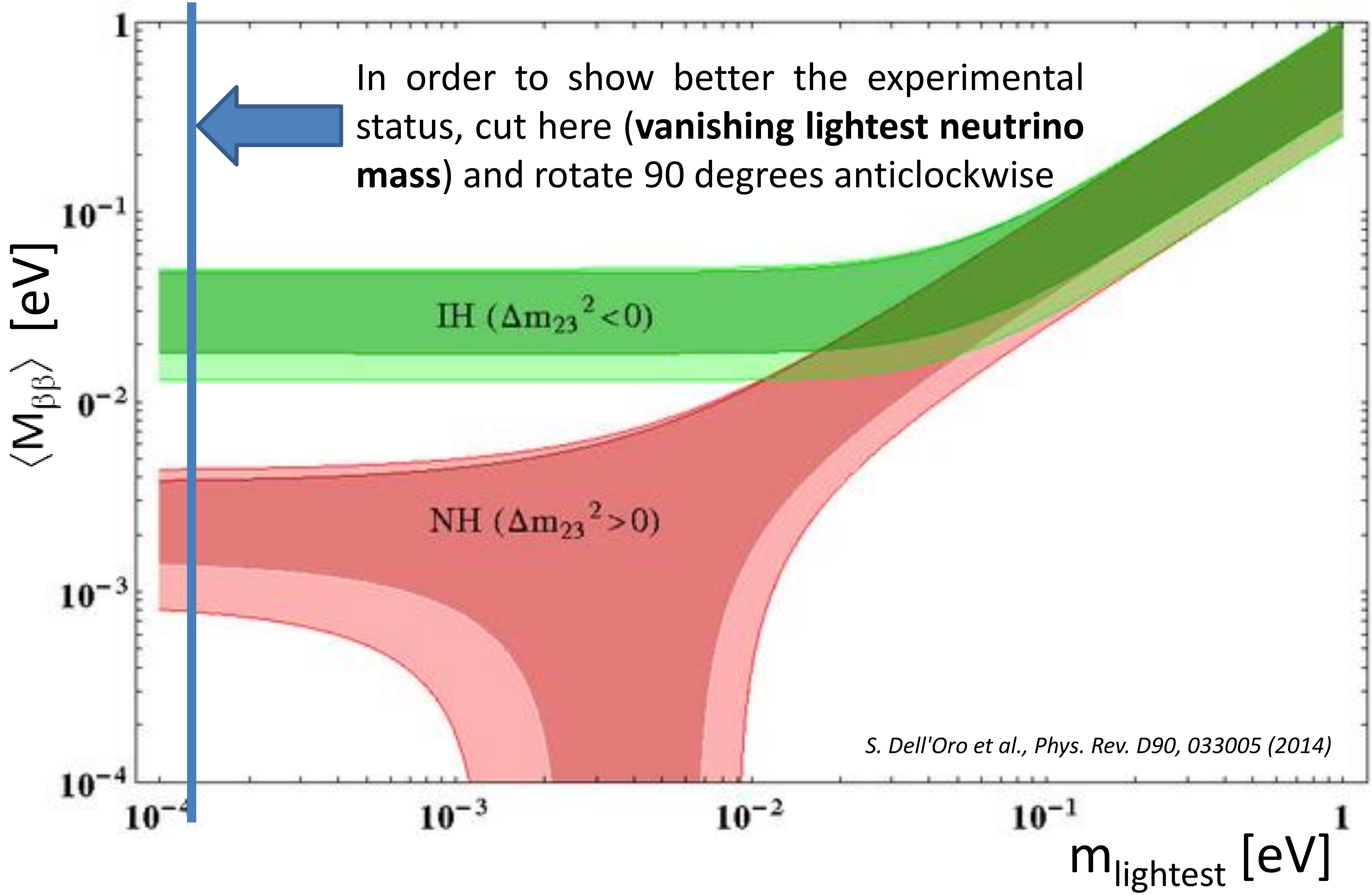
This is the realm of **scintillating bolometers** **(ZnSe, $ZnMoO_4$, $CdWO_4$) (CUPID, AMoRE)** , which offer:

- Source=detector
- High energy resolution - $\Delta E<<1\%$
- Full alpha rejection

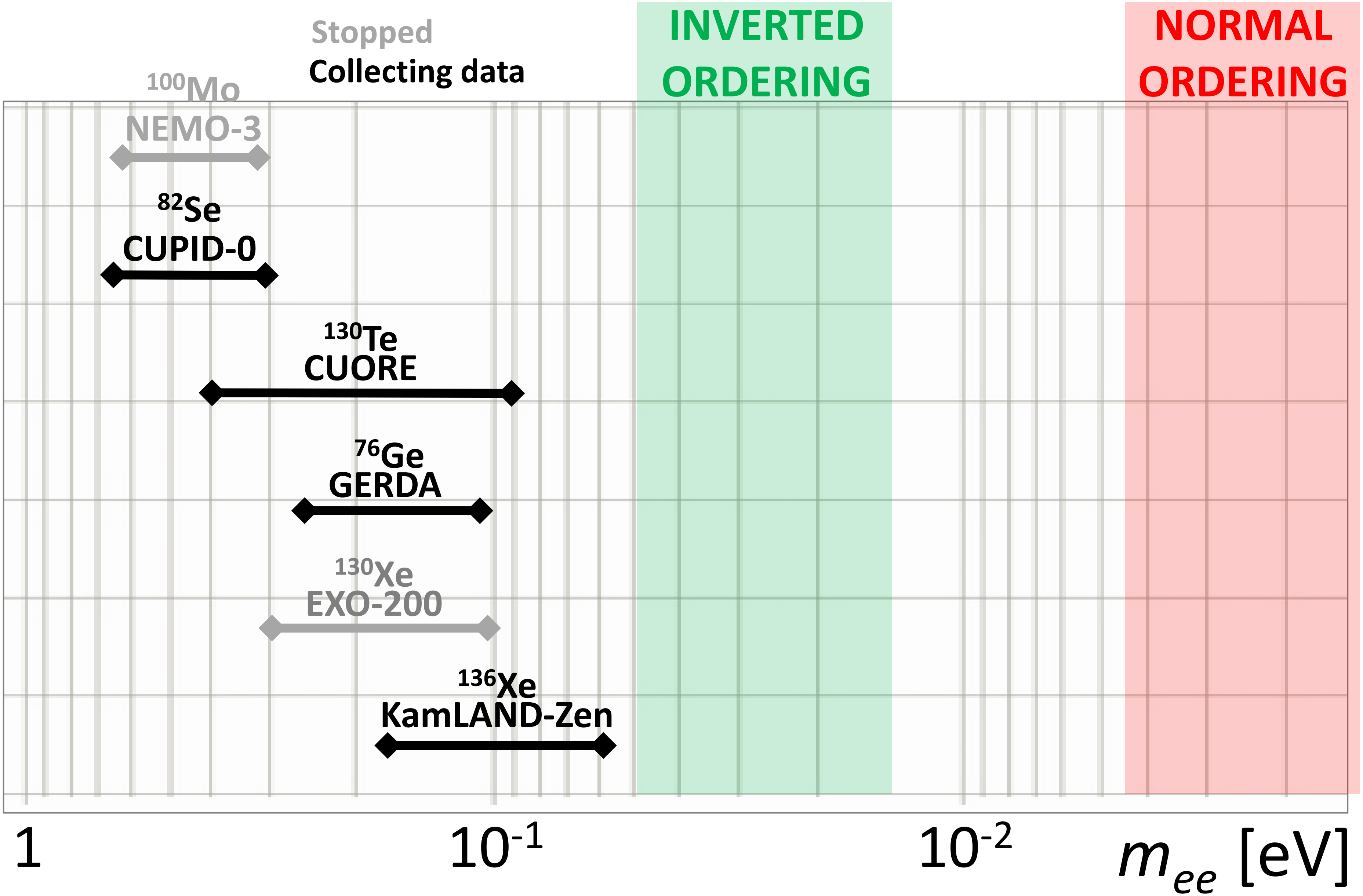
**$^{82}$Se** is the baseline option for **SuperNEMO**

In red, based on the bolometric technique

# $m_{ee}$ vs. lightest ν mass



# Current situation



# Approaches and experiments

**source = detector**

| | | | NOW | MID-TERM | LONG-TERM |
|---|---|---|---|---|---|
| Scalability | **Fluid embedded source** | Xe-based TPC | EXO-200<br>NEXT-10 | NEXT-100<br>PandaX-III | nEXO<br>NEXT-2.0<br>NEXT-HD<br>NEXT-BOLD<br>PandaX-III 1t |
| | | Liquid scintillator as a matrix | KamLAND-Zen 800<br>SNO+ phase I | | KamLAND2-Zen<br>SNO+ phase II |
| High $\Delta E$ and $\varepsilon$ | **Crystal embedded source** | Germanium diodes | GERDA-II<br>MAJORANA DEM. | LEGEND 200 | LEGEND 1000 |
| | | Bolometers | AMoRE pilot, I<br>CUORE<br>CUPID-0, CUPID-Mo | AMoRE II | CUPID<br>CUPID-reach<br>CUPID-1T |

# Current situation

**source = detector**

| | | NOW | MID-TERM | LONG-TERM |
|---|---|---|---|---|
| **Fluid embedded source** | Xe-based TPC | EXO-200<br>NEXT-10 | NEXT-100<br>PandaX-III | nEXO<br>NEXT-2.0<br>NEXT-HD<br>NEXT-BOLD<br>PandaX-III 1t |
| | Liquid | KamLAND-Zen 800 | | KamLAND2-Zen<br>SNO+ phase II |
| **embedded source** | | | | LEGEND 1000 |
| | Bolometers | AMoRE pilot, I<br>CUORE<br>CUPID-0, CUPID-Mo | AMoRE II | CUPID<br>CUPID-reach<br>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 – $m_{ee} < \sim 20$ meV**

# Approaches and experiments

| source = detector | | | NOW | MID-TERM | LONG-TERM |
|---|---|---|---|---|---|
| Scalability | **Fluid embedded source** | Xe-based TPC<br>scintillator as a matrix | EXO-200<br>NEXT-10<br>SNO+ phase I | NEXT-1 | |
| High $\Delta E$ and $\varepsilon$ | **Crystal embedded source** | Germanium diodes | GERDA-II<br>MAJORANA DEM. | LEGEND 200 | LEGEND 1000 |
| | | Bolometers | AMoRE pilot, I<br>CUORE<br>CUPID-0, CUPID-Mo | AMoRE II<br>CUPID | CUPID-reach<br>CUPID-1T |



# Approaches and experiments

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

Scalability

**Fluid embedded source**

Xe-based TPC


scintillator as a matrix

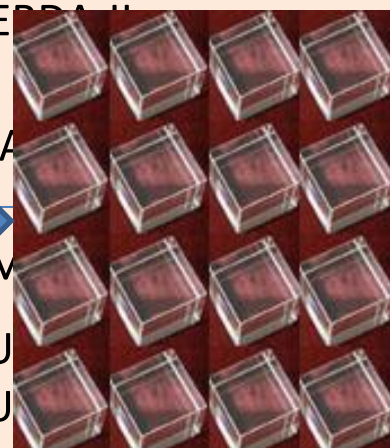
EXO-200

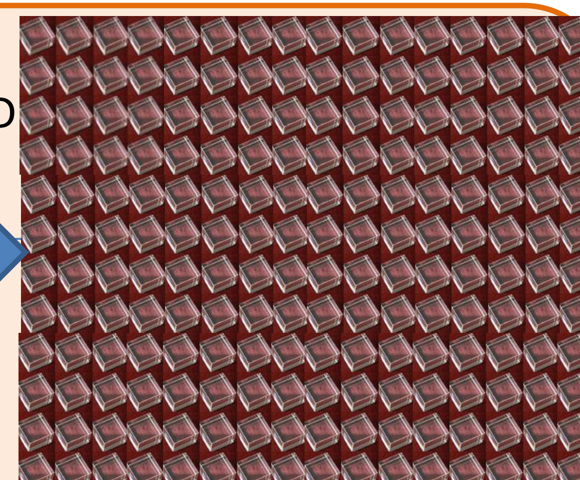

SNO+ phase I


High ΔE and ε

**Crystal embedded source**

Germanium





# 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

**High $\Delta E$ and $\varepsilon$**

Germanium | GERDA-II | LEGEND 200 | LEGEND 1000

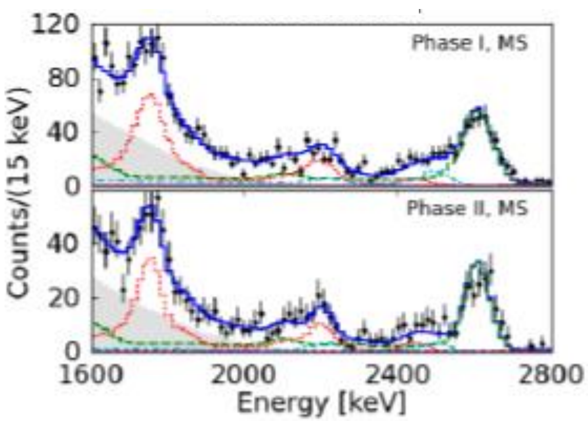
- High geometrical efficiency (> 70%)
- High energy resolution –3 keV FWHM in Ge diodes – 5 keV FWHM in bolometers
- Granularity, pulse shape discrimination, particle identification methods
- The limit (signal) comes from a narrow region around the Q value
- The background model is used mainly to understand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

CUPID-1T

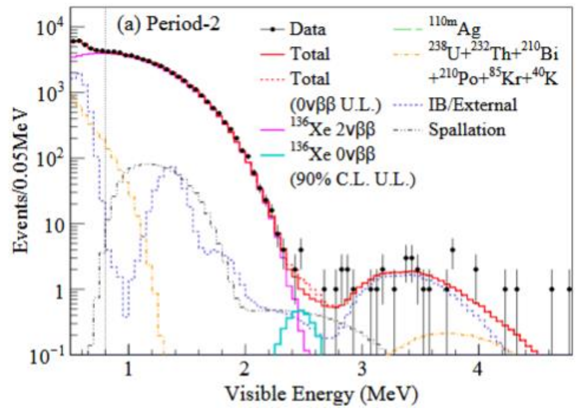
# Approaches and experiments

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

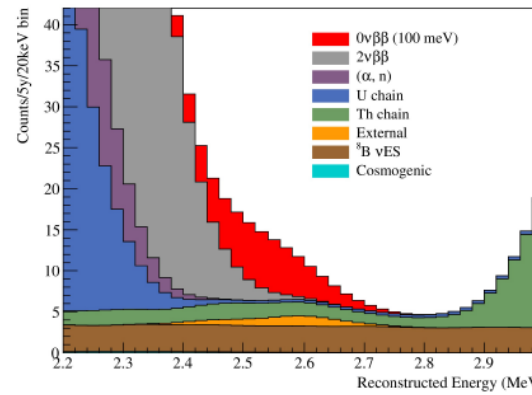
EXO-200




KamLAMD-Zen

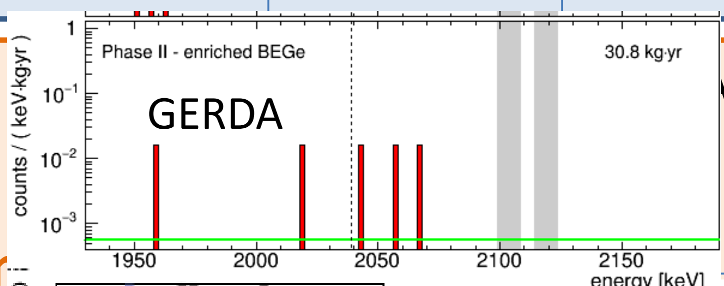



SNO+

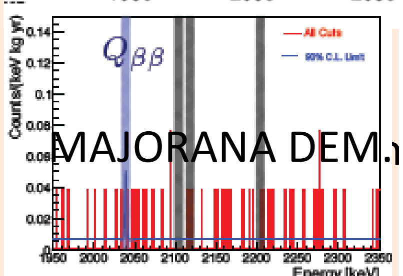



High ΔE and ε

GERDA

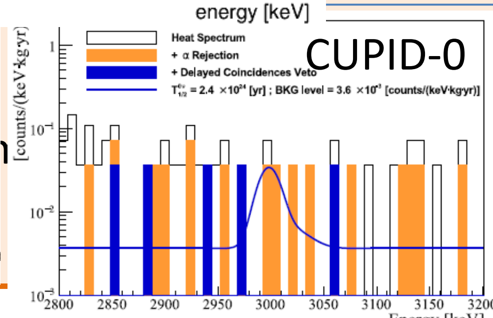



MAJORANA DEM.

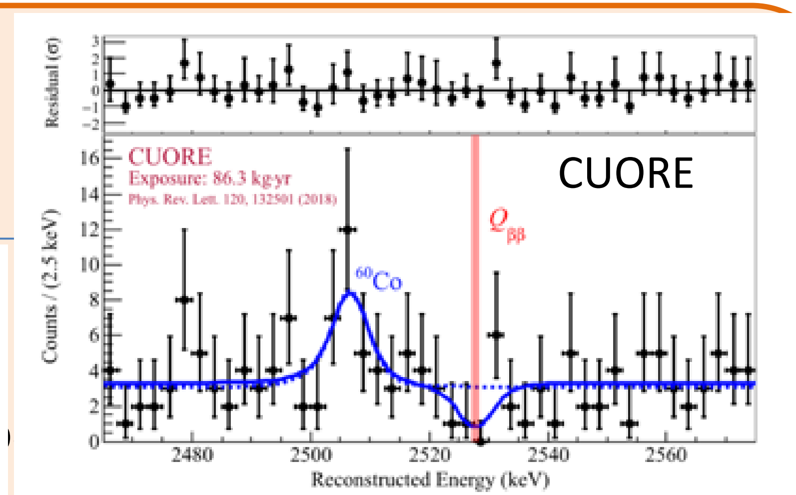



MAJORANA

CUPID-0




CUORE



# Outline

- Double beta decay: what it is and why it is important
- How we search for neutrinoless double beta decay
- Overview of the current experimental situation
- Details of the most important experiments
- Challenges for the future

# EXO-200

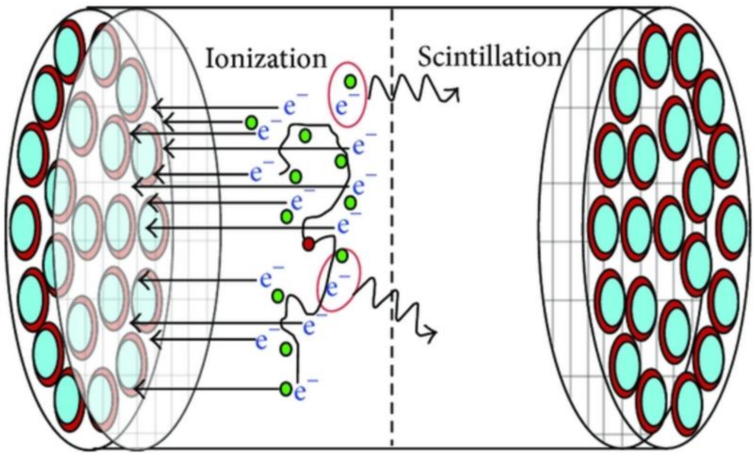
**EXO-200 has recently completed data taking**

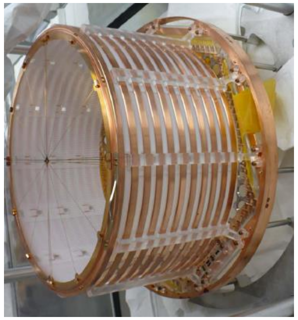
**WIPP - US**

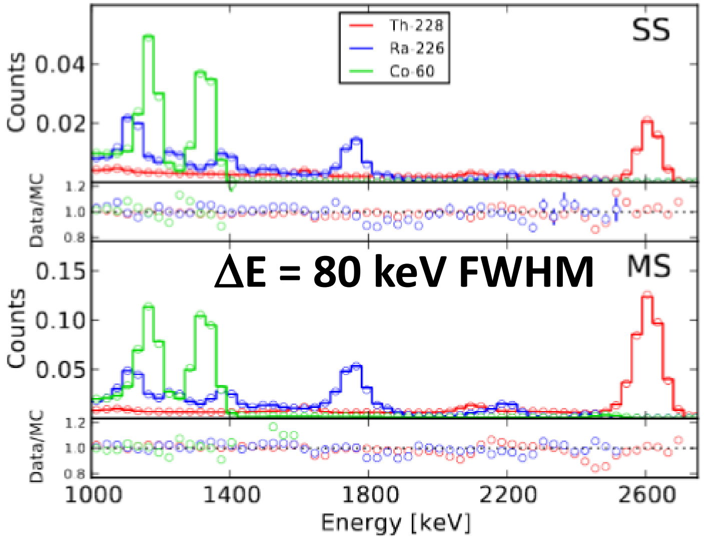
Final results: **$T_{1/2} > 3.5\times10^{25}$ y**

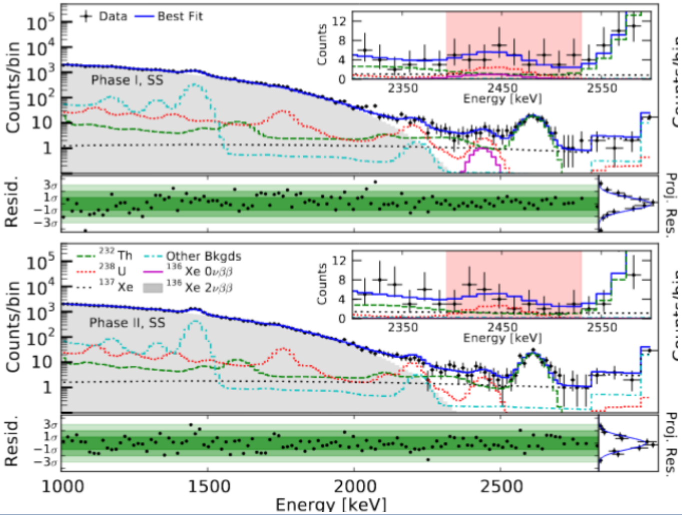
**$m_{ee} < 107 – 290$ meV**

**Enriched liquid xenon TPC**





# EXO-200 → nEXO

**EXO-200 has recently completed data taking**

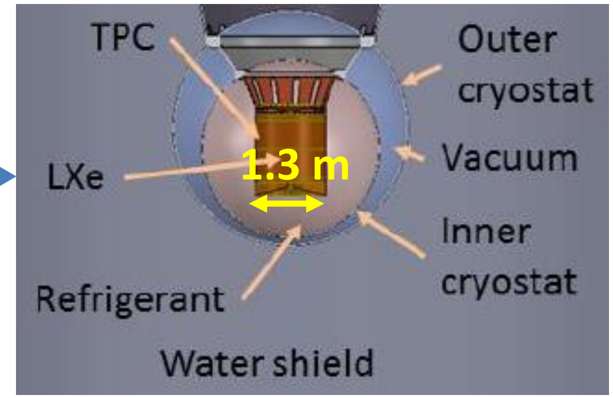
**WIPP - US**

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

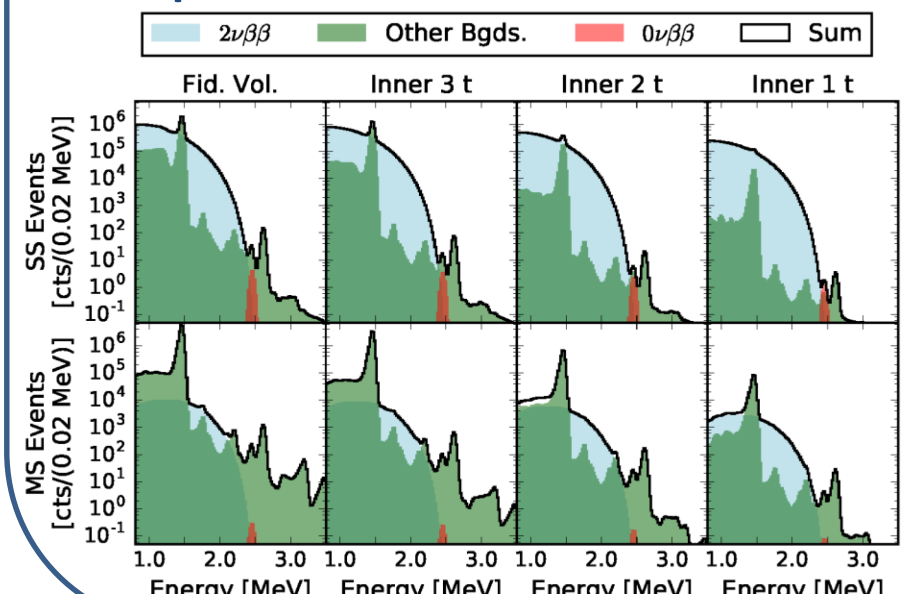
$m_{ee} < 107 – 290$ meV

## Moving forwards towards nEXO

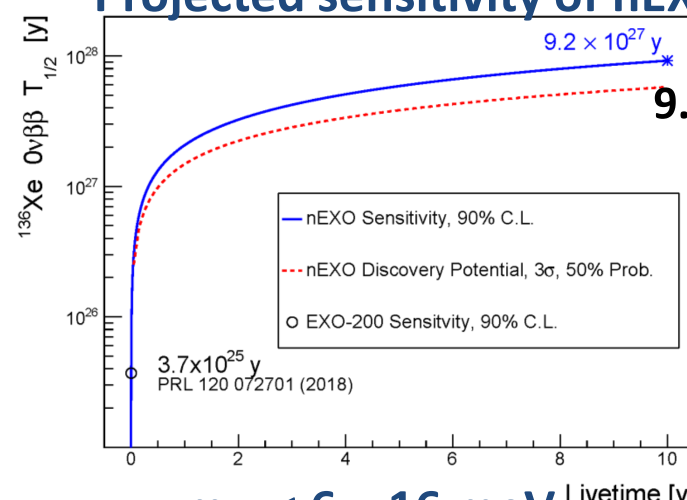
| LXe mass (kg) | Diameter or length (cm) |
|---|---|
| 5000 | 130 ~nEXO |
| 150 | 40~ EXO-200 |




## Importance of fiducialization




## Projected sensitivity of nEXO



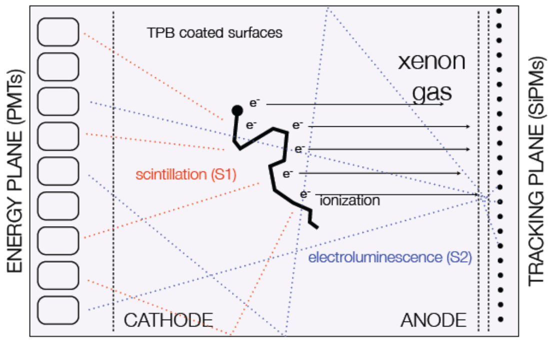

**$9.2 \times 10^{27}$ y**

$m_{ee} < 6 – 16$ meV

# NEXT

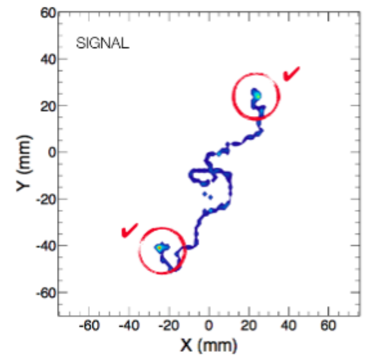
## High pressure (10-15 bar) enriched Xe TPC

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




## 5 kg working prototype with $^{nat}Xe$

- **ΔE < 1% FWHM** in the ROI (< 25 keV)
- Very clear topological signature
- Enriched Xe run has started in 2019




**Canfranc – Spain**

## NEXT 100

**Canfranc – Spain**

- Many detector elements available
- Commissioning in 2019

**5 y sensitivity: $T_{1/2} > 1\times10^{26}$ y**

**$m_{ee} < 46 – 170$ meV**

## Medium-term prospects – NEXT-HD

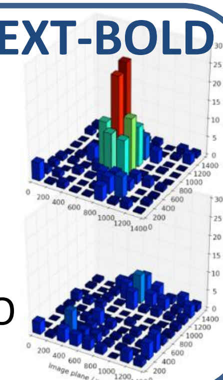
- Ton scale
- High definition tracks (He-Xe mixture)
- Si-PM instead of PM (better background)
- **5 y sensitivity: $T_{1/2} > 1\times10^{27}$**

## Long-term prospects – NEXT-BOLD

### Ba-tagging

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

Results both by NEXT and nEXO

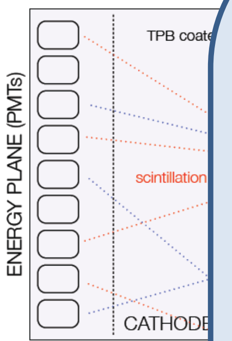


# NEXT



## High pressure (10-15 bar) enriched Xe TPC

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

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- Very clear topological signature

rted in 2019

anfranc – Spain

## NEXT 100

- Many detector
- Commissioning

$0^{26}$ y

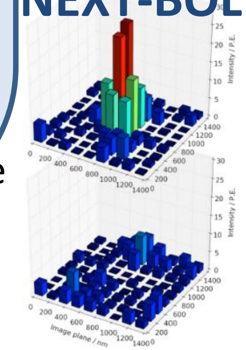
## Medium-term

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

## NEXT-BOLD

ce

using Single Molecule **Fluoresence Imaging**. To demonstrate in Xe gas.



**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

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

**KamLAND-Zen 400: data taking completed**

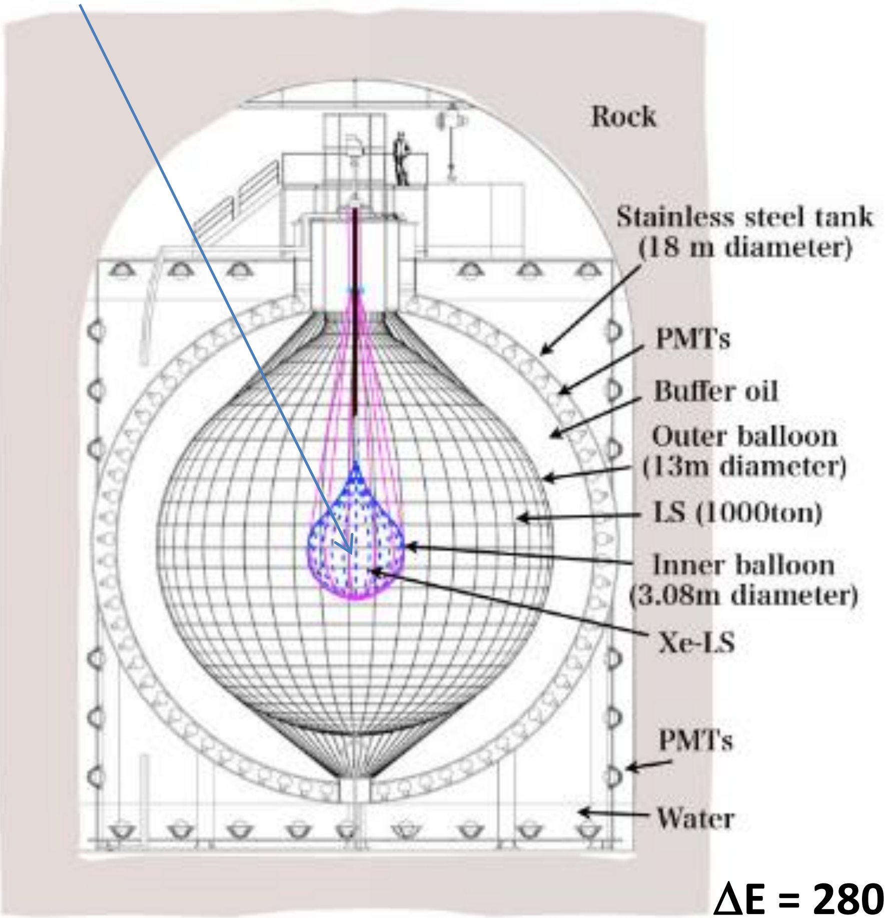
**Kamioka – Japan**

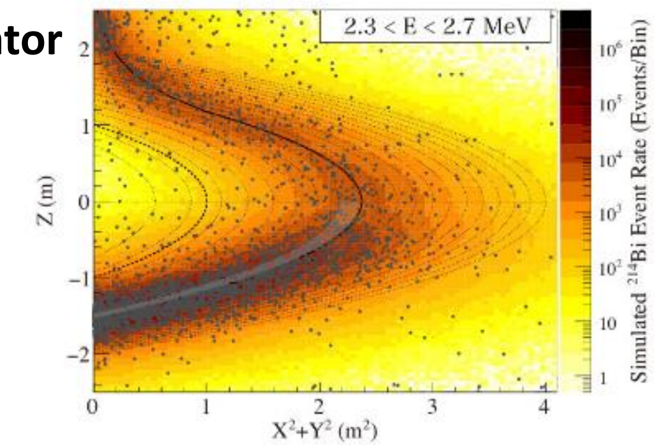
**Leading experiment**

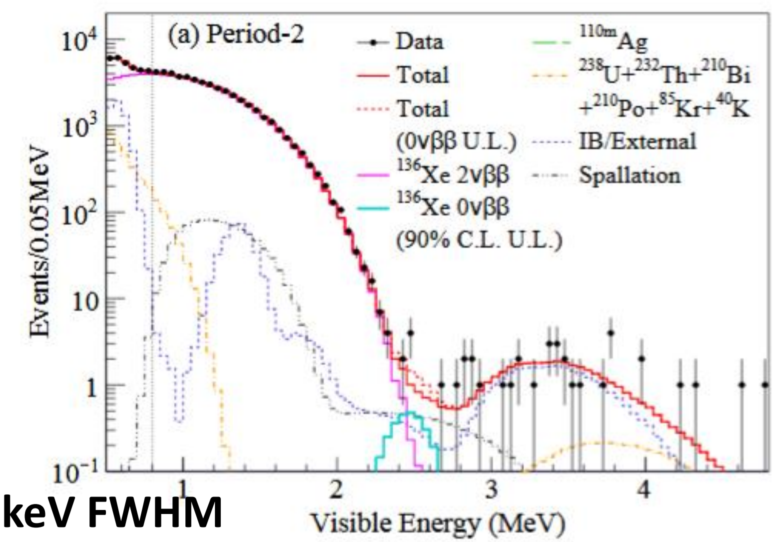
Results: $T_{1/2} > 1.07\times10^{26}$ y

$m_{ee} < 60 – 160$ meV

**Enriched Xenon (350 kg) diluted in liquid scintillator**




**ΔE = 280 keV FWHM**

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

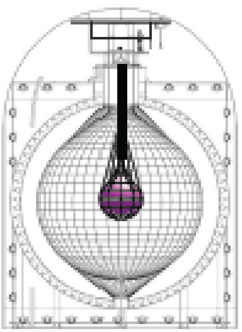
**KamLAND-Zen 400: data taking completed**

**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**

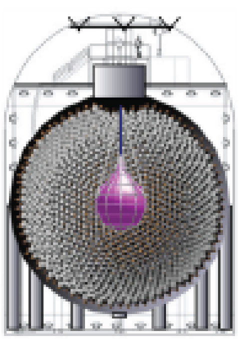
Similar to KamLAND-400

**Major new points:**

- More isotope – **750 kg of $^{136}Xe$**
- New balloon
- **$T_{1/2} > 4.6\times10^{26}$ y**

**$m_{ee} < 30 – 80$ meV**

**New experiment** → Substantiantial changes



Future

KamLAND2-Zen

~1 ton of $^{136}Xe$

Better energy resolution

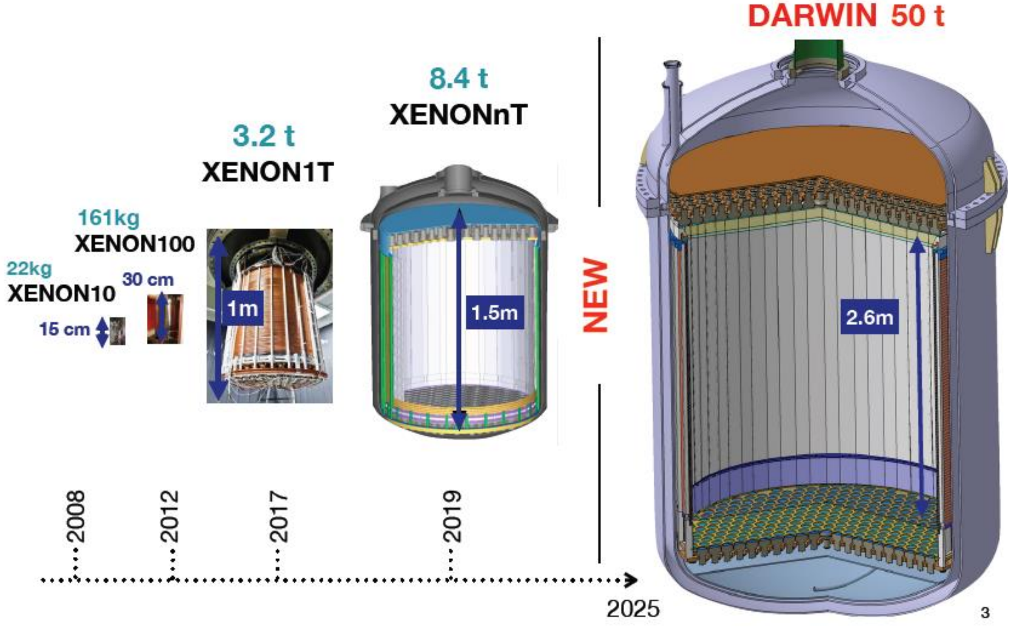
**Major new points:**

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

**$m_{ee} < 20$ meV**

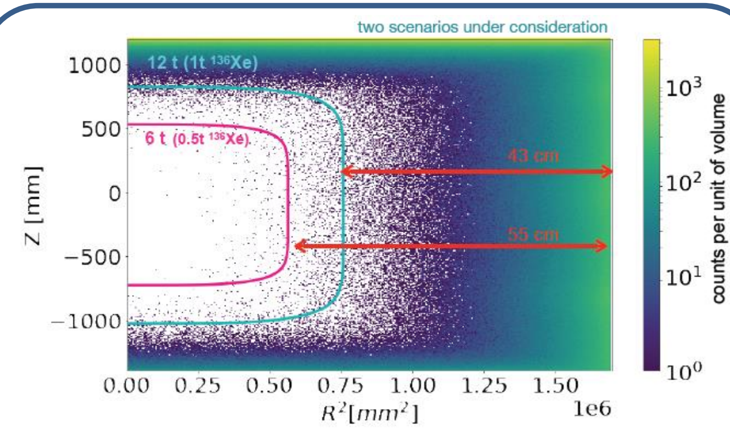
# DARWIN as a neutrinoless double beta decay experiment

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




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

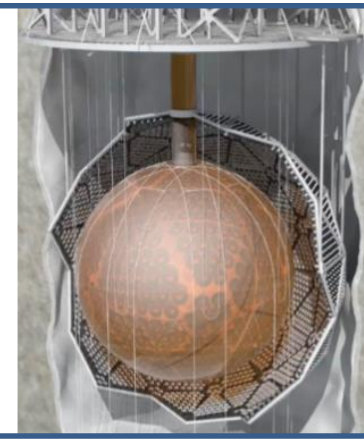
**10 y sensitivity: $T_{1/2} > 4\times10^{27}$ y**
**$m_{ee}$ < 11 – 25 meV**

# SNO+

**Re-use existing infrastructure of SNO – 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)

- Filling with liquid scintillator is in progress
- **$\Delta$E = 190 keV FWHM**
- **5 y sensitivity: $T_{1/2} > 1.9\times10^{26}$ y** **$m_{ee} < 35 – 140$ 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**

**$m_{ee} < 15 – 60$ 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 $\nu$'s $\rightarrow$ directional measurement**

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

**$m_{ee} < 5 – 18$ meV**

**without enrichement**

# GERDA, MAJORANA → LEGEND

## GERDA

Exposure: 82.4 kg × y

Background index: **$1.0^{+0.6}_{-0.4} \times 10^{-3}$ c/(keV kg y)**

**$T_{1/2} > 0.9 \times 10^{26}$ y**

**$m_{ee}$ < 110 – 260 meV**

## MAJORANA demonstrator

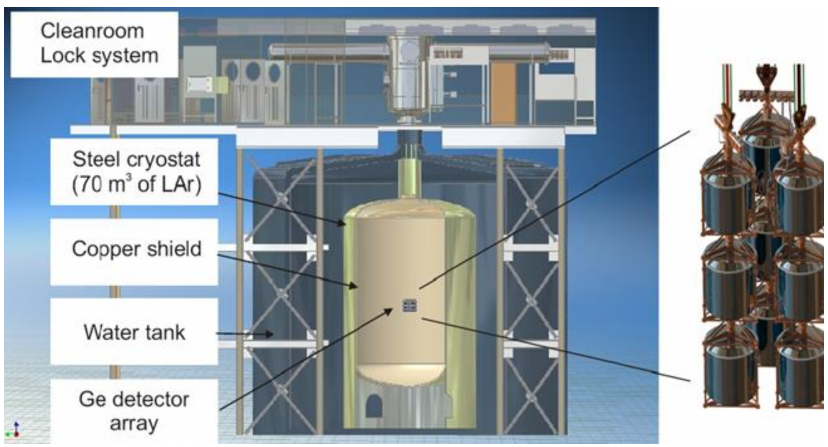
Exposure: 26 kg × y

Background: **$(4.7 \pm 0.8) \times 10^{-3}$ c/(keV kg y)**

**$T_{1/2} > 2.7 \times 10^{25}$ y**

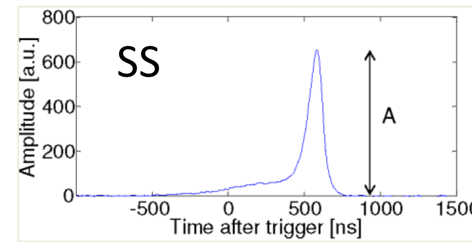
**$m_{ee}$ < 210 – 440 meV**

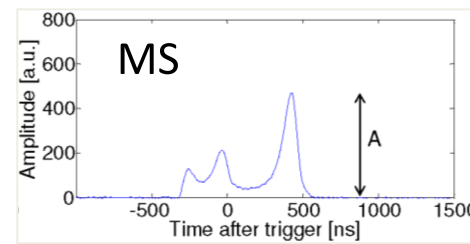
**37 HP Ge diodes immersed in LAr**

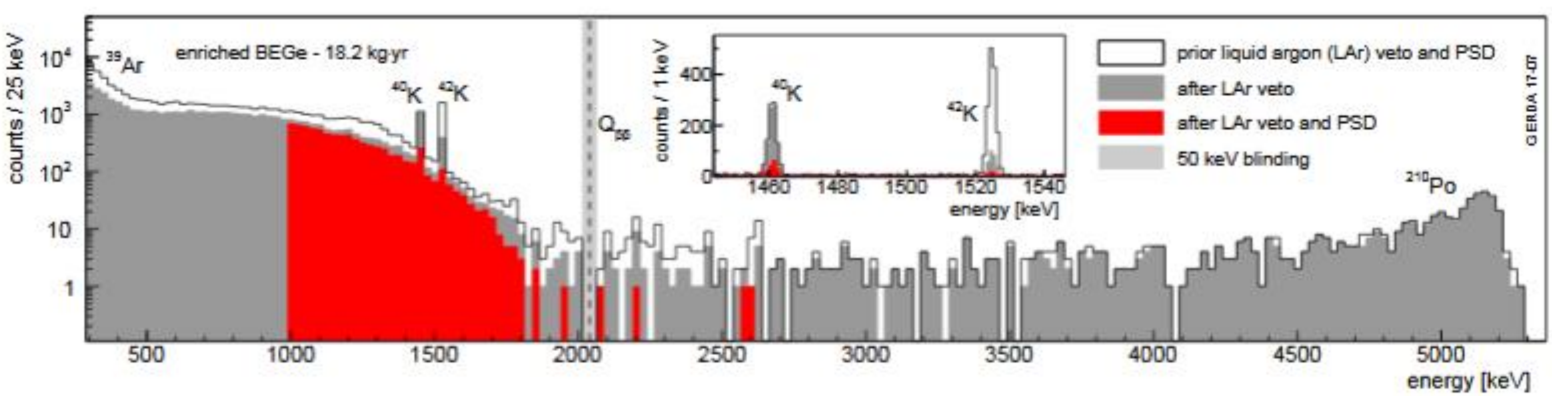



**35 kg of enriched Ge**

**ΔE = 3 keV FWHM**



# GERDA, MAJORANA → LEGEND

**GERDA**

Exposure: 82.4 kg × y

Background index: **$1.0^{+0.6}_{-0.4}$ × $10^{-3}$ c/(keV kg y)**

**$T_{1/2}$ > $0.9 \times 10^{26}$ y**

**$m_{ee}$ < 110 – 260 meV**

**MAJORANA demonstrator**

Exposure: 26 kg × y

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

**$T_{1/2}$ > $2.7 \times 10^{25}$ y**

**$m_{ee}$ < 210 – 440 meV**

## Combining the best of MAJORANA and GERDA → LEGEND

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

- 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 **> $10^{28}$ y**

**$m_{ee}$ < 11 – 23 meV**

# 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**: 0.6 counts/FWHM t yr (**3x lower than GERDA**)
- Data-taking could start as early as 2021
- **Sensitivity: > $10^{27}$ y for 1 tonne × y** **$m_{ee}$ < 35 – 75 meV**

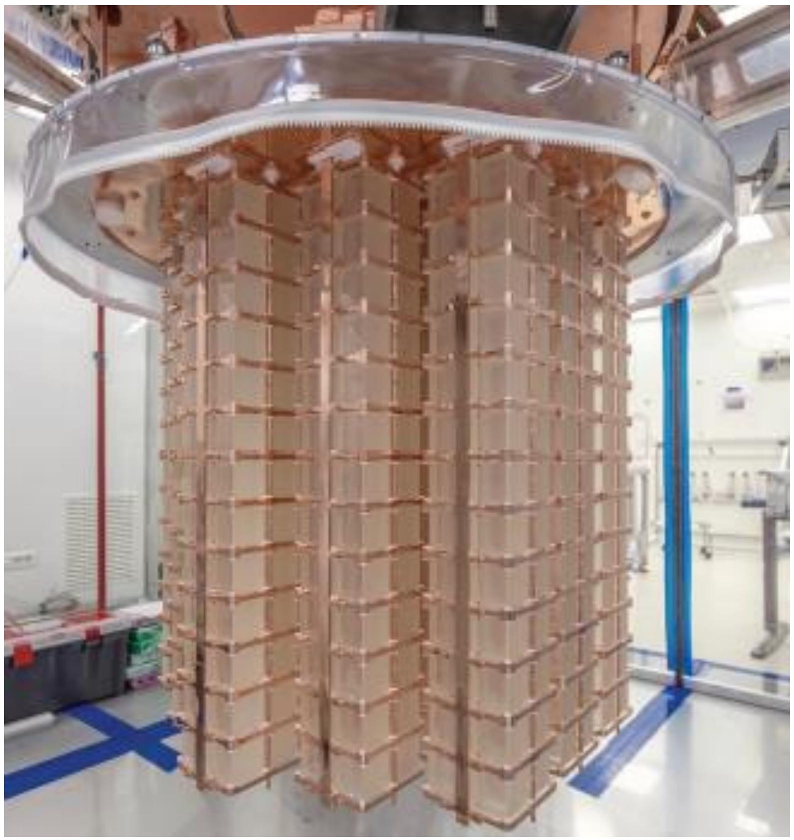
## LEGEND-1000:

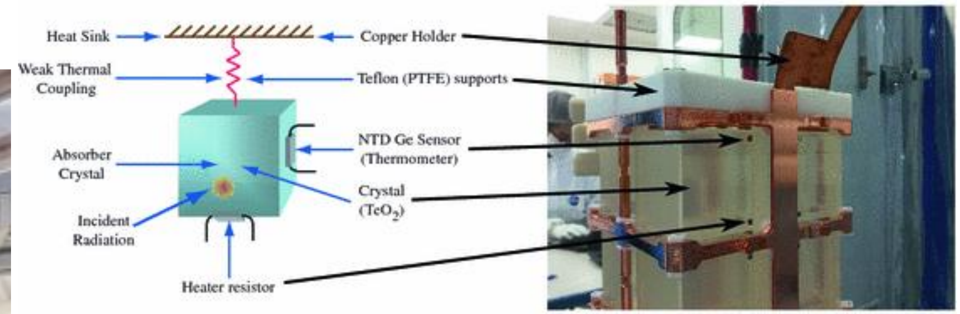
- **1000 kg (phased)** required to cover neutrino-mass I
- **Sensitivity: > $10^{28}$ y**
- Background goal: a factor 10 lower wrt LEGEND-200 → **background free at 10 ton × y**
- Location under discussion
- Required depth under investigation

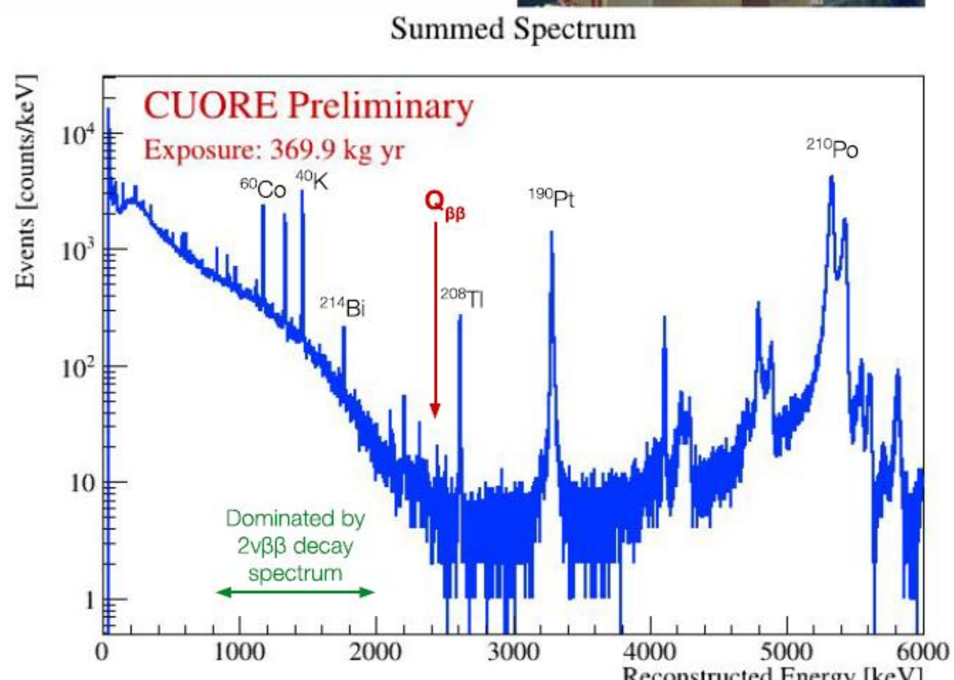
# CUORE



**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 $^{130}Te$**





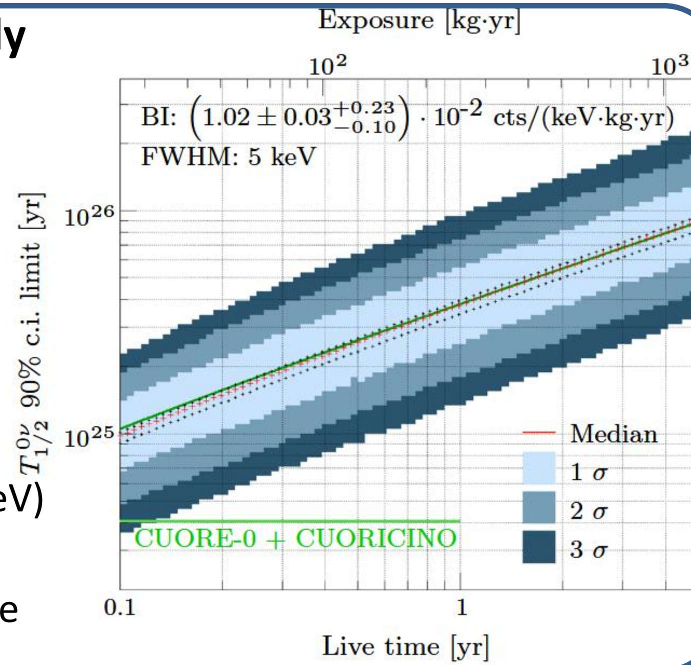
$^{130}$Te, $^{100}$Mo

# CUORE → CUPID

**LNGS – Italy**

## CUORE is collecting data succesfully

- Exposure: 369.9 kg × y - $T_{1/2}$ > 2.3×$10^{25}$ y
  $m_{ee}$ < 90 – 420 meV PRELIMINARY
- 5 y projected half-life sensitivity: ~$10^{26}$ y
  → $m_{ee}$ < 50 – 190 meV
  - Background close to expectations: **b = 1.4 × $10^{-2}$ c/(keV·kg·yr)**
  - Energy worse than expectations and CUORE-0 (5 keV) **~8.7 keV FHWM** → margins for improvement
  - Analysis of **~1000 individual bolometers** is handable




## Two 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**

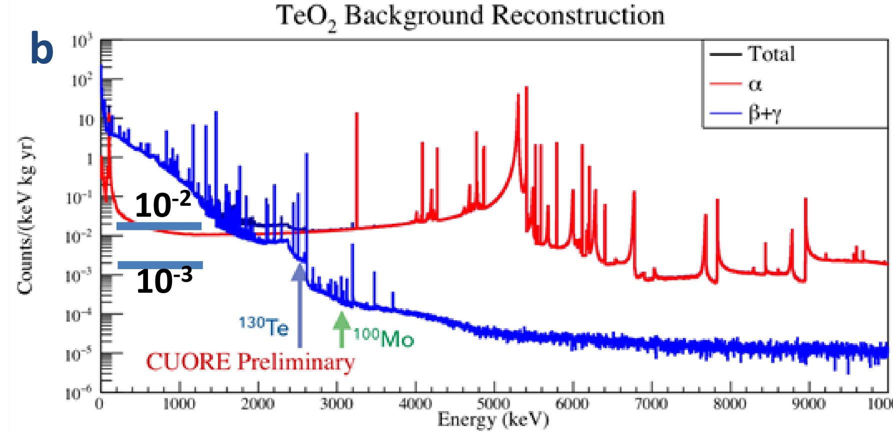
# CUPID is the natural evolution of CUORE

$^{82}$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 )

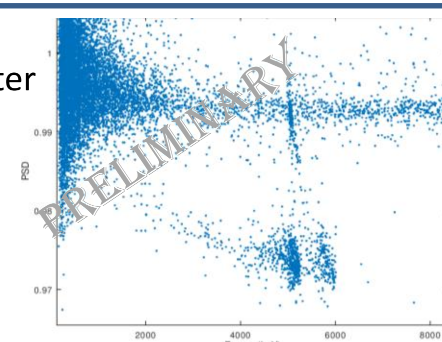
**$^{116}$Cd in scintillating $CdWO_4$ crystals** → R&D in LSM (Modane) and LSC (Canfranc)

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

**CROSS** erc

Less mature but resolving alternative: reject **surface events** by **PSD**

PSD parameter




← bulk

← surface

# CUPID demonstrators



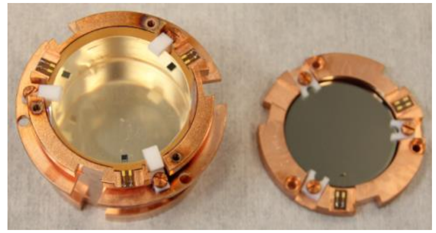
**Scintillating bolometers**

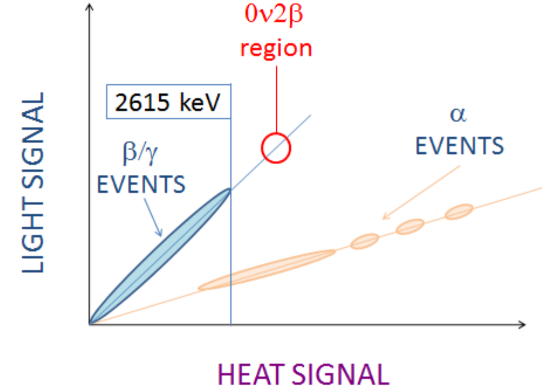
↓

**α particle rejection**

Main crystal

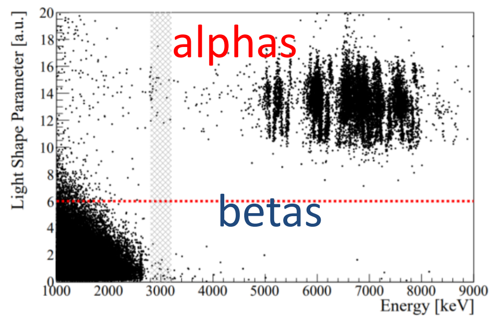
Light detector

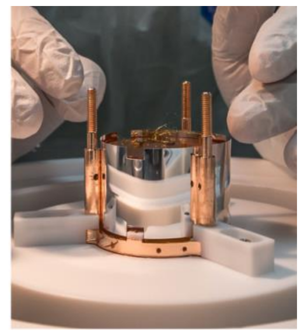





## CUPID-0 – $Zn^{82}Se$  Q=2998 keV

**First running demonstrator** - LNGS
24 crystals – 5.28 kg $^{82}Se$
Best limit on $^{82}Se$: $T_{1/2} > 3.5\times10^{24}$ **y**
Energy resolution: **~23 keV FWHM**
**Required improvements in crystal quality and radiopurity**



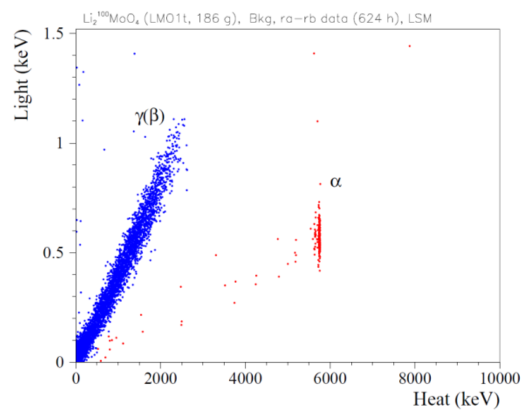
**LNGS – Italy**

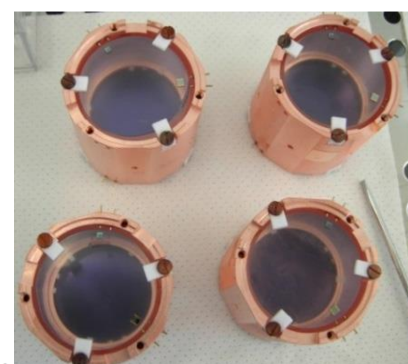
**b = 3.5 × $10^{-3}$ c/(keV·kg·yr)**

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

**LSM – France**

**Phase-I 20 crystals** – 2.34 kg $^{100}Mo$
currently in data taking
**Phase-II**
additional ~30 crystals – 4 kg $^{100}Mo$
LNGS (CUPID-0 setup) or LSC (CROSS set-up)
Energy resolution: **~5 keV FWHM**
**Radiopure high-quality crystals**
**Negligible $^{100}Mo$ losses in crystal growth**



$^{82}$Se, $^{100}$Mo

# CUPID demonstrators

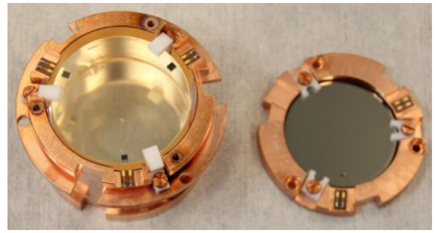
**Scintillating bolometers**

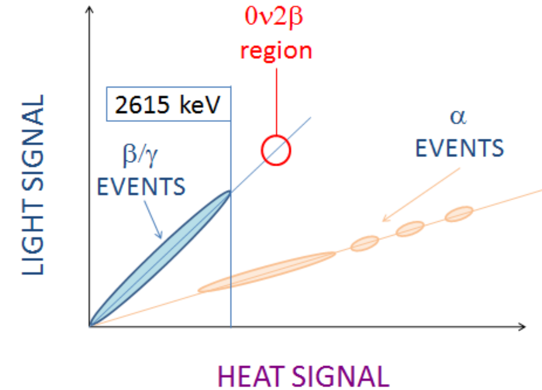
⬇

**α particle rejection**

Main crystal

Light detector






## CUPID-0 – Zn$^{82}$Se Q=2998 keV

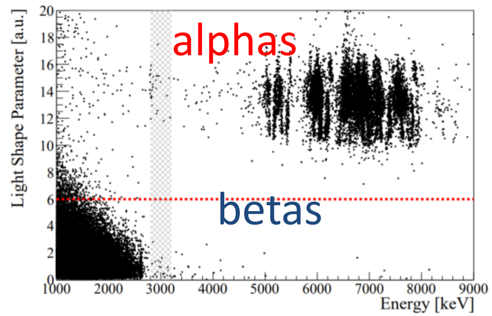
**First running demonstrator** - LNGS

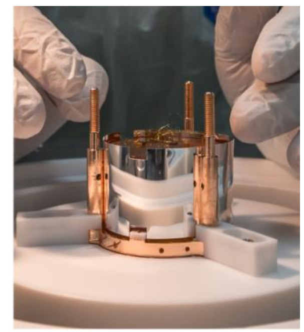
24 crystals – 5.28 kg $^{82}$Se

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**



**LNGS – Italy**

**b = 3.5 × 10$^{-3}$ c/(keV·kg·yr)**

## CUPID-Mo – Li$_2$$^{100}$MoO$_4$ Q=3034 keV

**LSM – France**

**Phase-I 20 crystals** – 2.34 kg $^{100}$Mo
currently in data taking

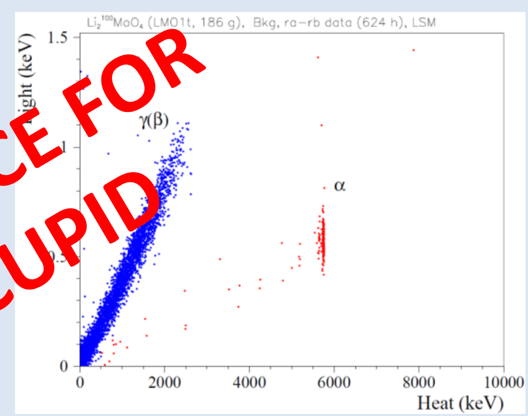
**Phase-II**
additional ~30 crystals – 4 kg $^{100}$Mo
LNGS (CUPID-0 setup) or LSC (CROSS set-up)

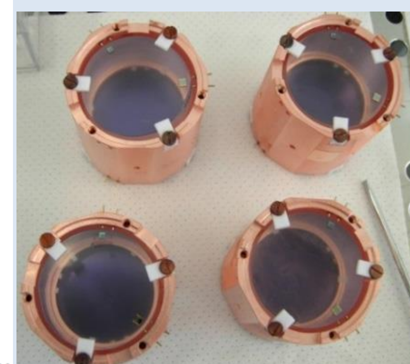
Energy resolution: **~5 keV FWHM**

**Radiopure high-quality crystals**

**Negligible $^{100}$Mo losses in crystal growth**

**CHOICE FOR CUPID**



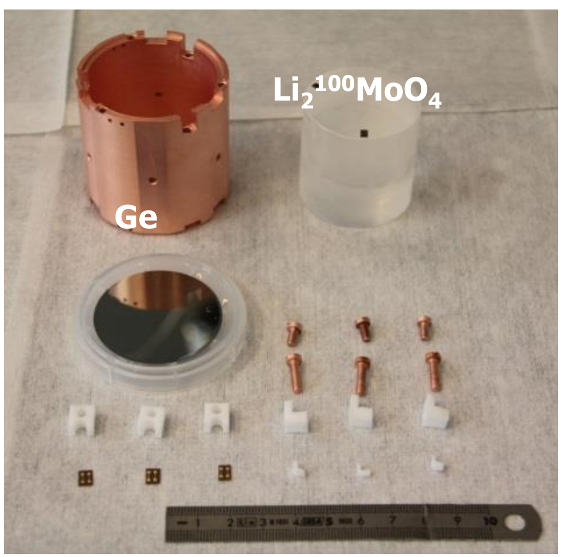
# CUPID-Mo

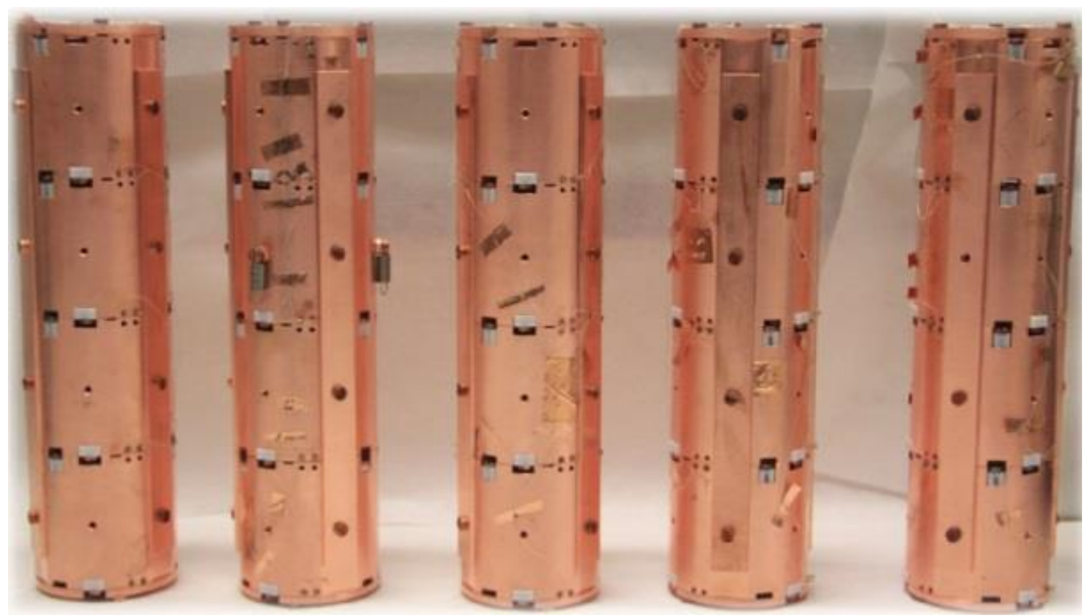
- High-sensitivity search for double beta decay of $^{100}Mo$
- Installed in the **Modane** underground laboratory (France)
- It coexists in the same cryostat as the EDELWEISS dark matter experiment
- Regular data taking since April 2019
- Evolution of **LUMINEU** and demonstrator for **CUPID**

**20-scintillating-bolometer array**

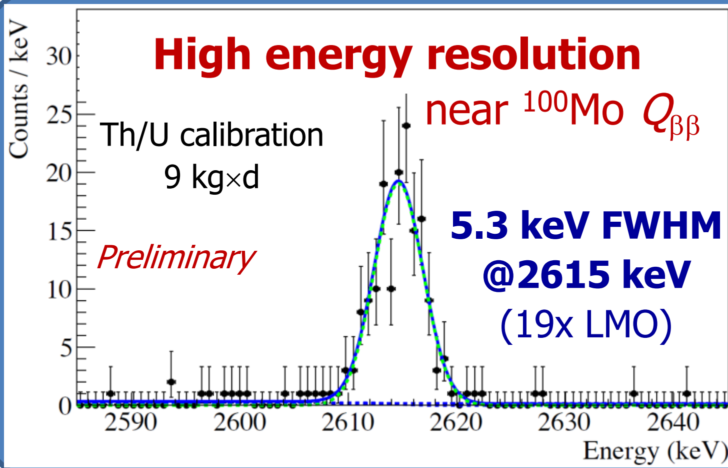
**20x 0.2-kg $Li_2{}^{100}MoO_4$**

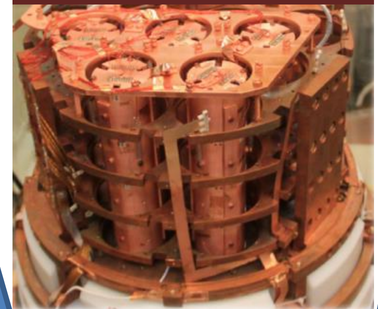
**2.26 kg $^{100}Mo$**



# CUPID-Mo

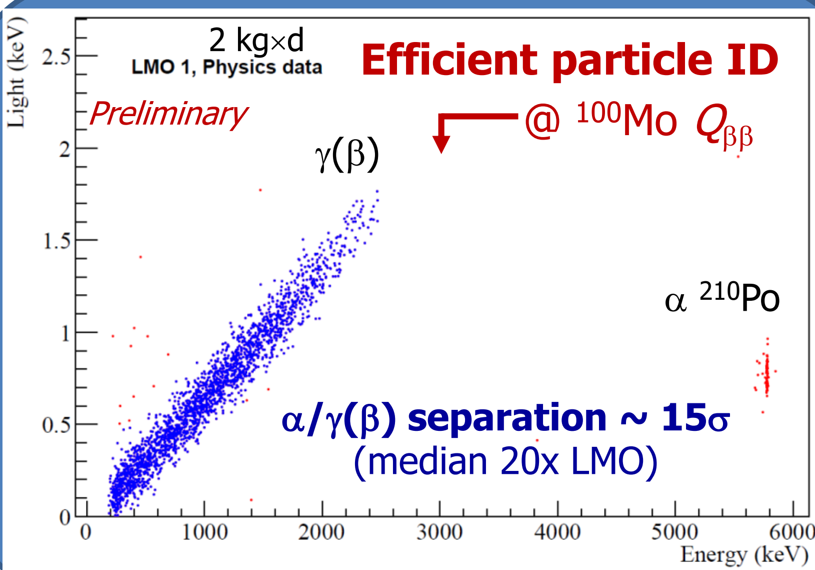


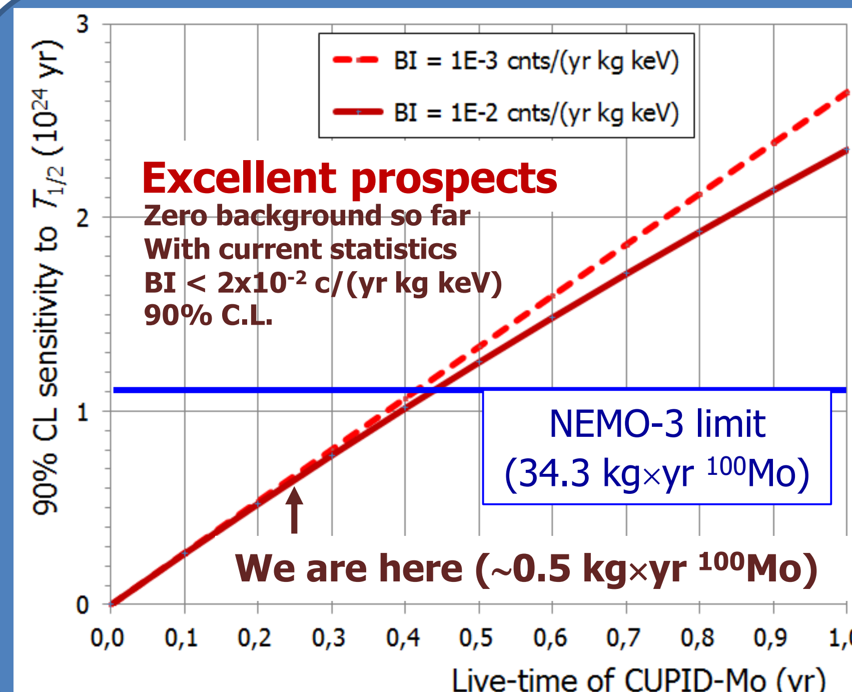



## High crystal radiopurity

| Chain | Nuclide | Activity [μBq/kg] |
|---|---|---|
| $^{238}$U | $^{210}$Po | ~ $10^2$ |
| | $^{226}$Ra | < 3 |
| $^{232}$Th | $^{232}$Th | < 1 |

**20 $Li_2{}^{100}MoO_4$ scintillating bolometers** → **$^{100}$Mo 0νββ search**

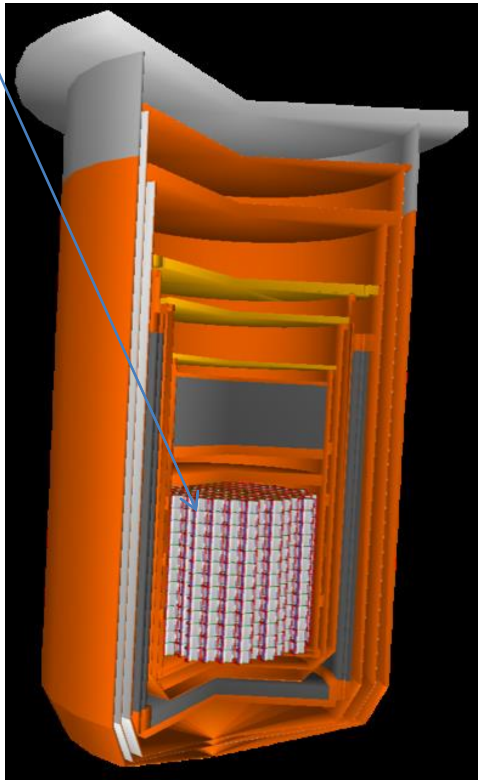


# CUPID configuration and reach



- Single module: $Li_2{}^{100}MoO_4$ **Ø50×50 mm**
- 118 towers of 13 floors each - **1534 crystals**
- **~250 kg of $^{100}$Mo** for >95% enrichment
- **$1.6\times10^{27}$** $^{100}$Mo atoms

**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-0 and CUPID-Mo data

**CUPID** 10 y half-life sensitivity:

$$T_{1/2} > 1.5 \times 10^{27}\ y$$

$$\rightarrow m_{ee} < 10 - 17\ meV$$

**CUPID-reach** - Bkg improvement by factor 5

**$2.3 \times 10^{27}$ y** $\rightarrow$ **$m_{ee} < 8.2 - 14$ meV**

**CUPID-1 T** - Bkg improvement by factor 20

1 ton isotope $\rightarrow$ new cryostat

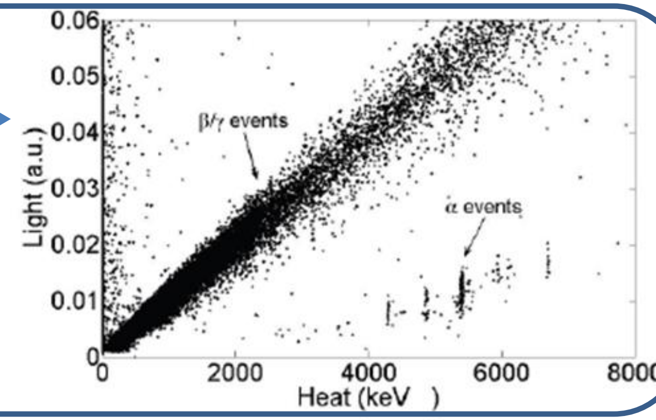
**$9.2 \times 10^{27}$ y** $\rightarrow$ **$m_{ee} < 4.1 - 6.8$ meV**

# AMoRE

**Detector concept**

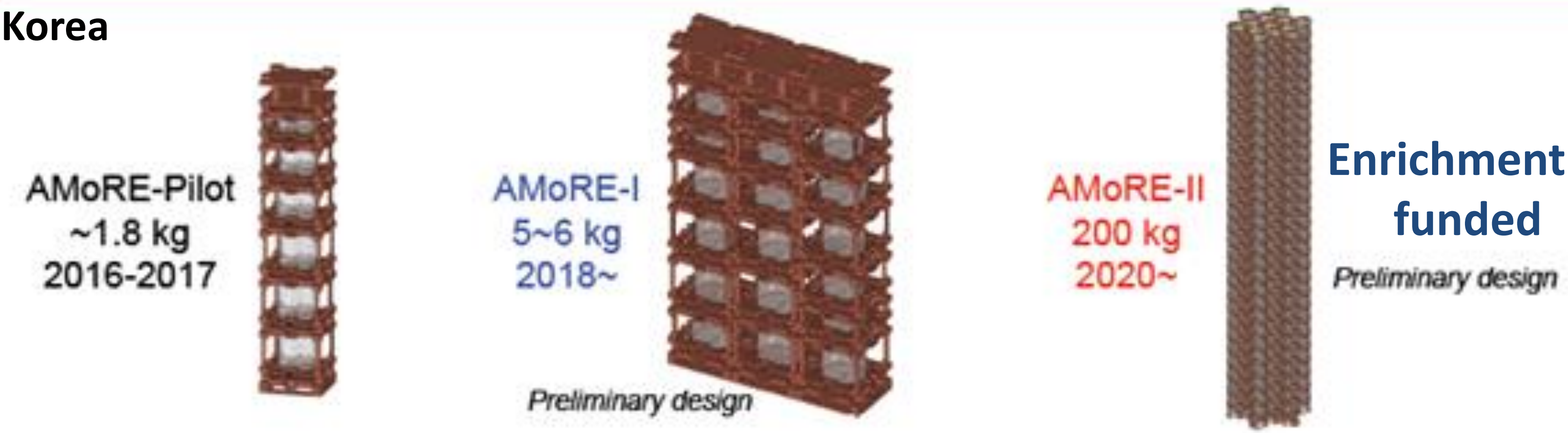
scintillating bolometers based on **$Ca^{100}MoO_4$**

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




- 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**




**Enrichment is funded**

**Target sensitivities:** **$10^{25}$ y** **$5 \times 10^{26}$ y**

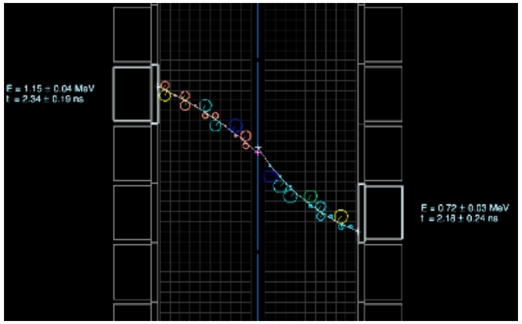
$m_{ee} < 120 – 200$ meV $m_{ee} < 17 – 30$ meV

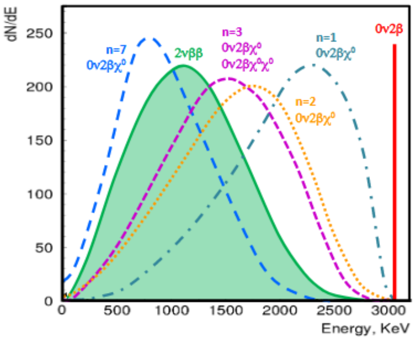
**source ≠ detector**

# 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**

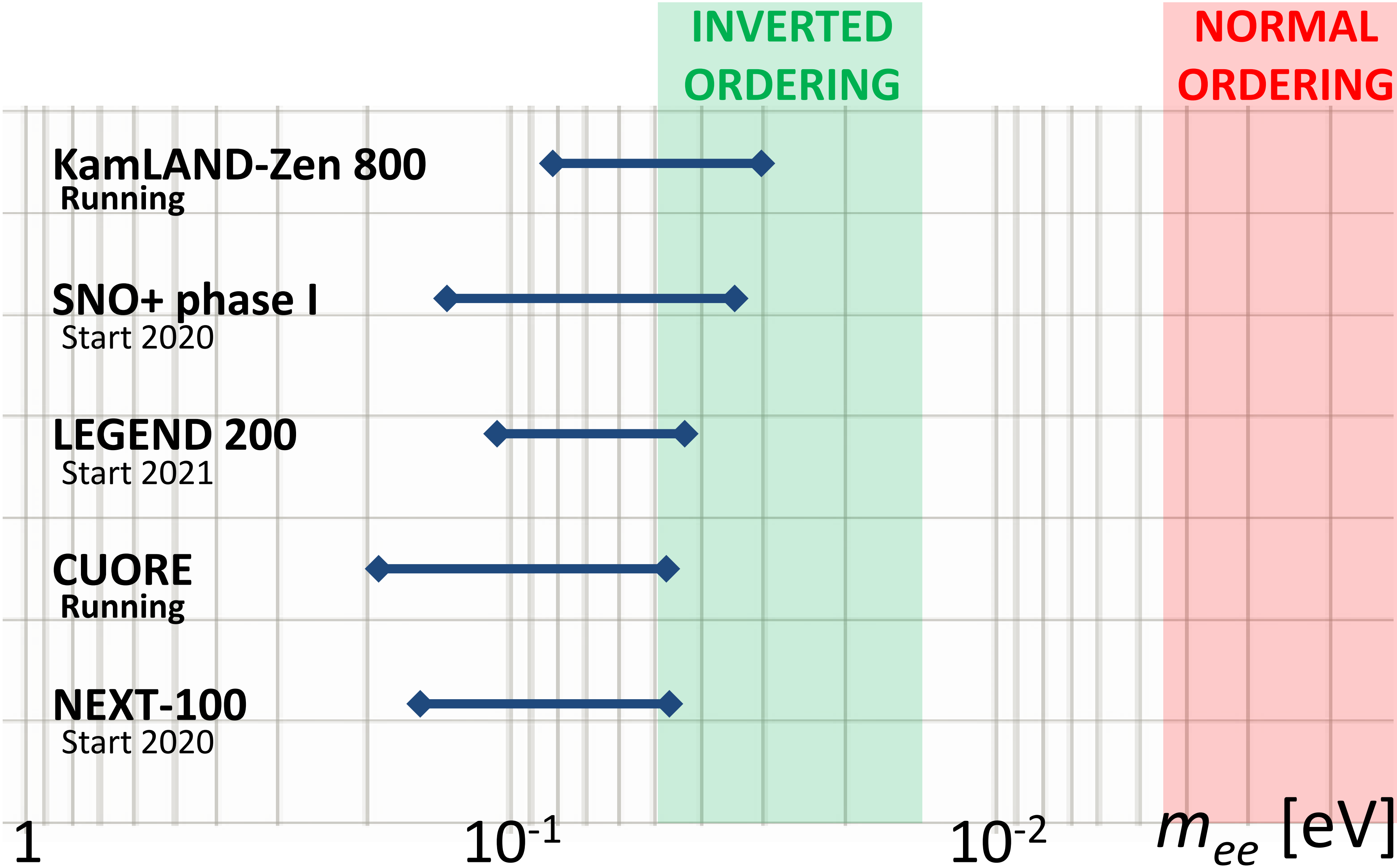
- The idea to build full SuperNEMO (20 module – 100 kg) is abandoned
  non competitive in the current scenario
- Plans to move to **$^{150}$Nd** – enrichment by centrifugation is expensive but now possible
  → **higher phase space by a factor 6 – Rn free background**
- Keep technology ready in case of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

# Outline

- Double beta decay: what it is and why it is important
- How we search for neutrinoless double beta decay
- Overview of the current experimental situation
- Details of the most important experiments
- Challenges for the future

# Possible scenario in 2025

Considering running or well advanced projects (for results, funding and infrastructures)



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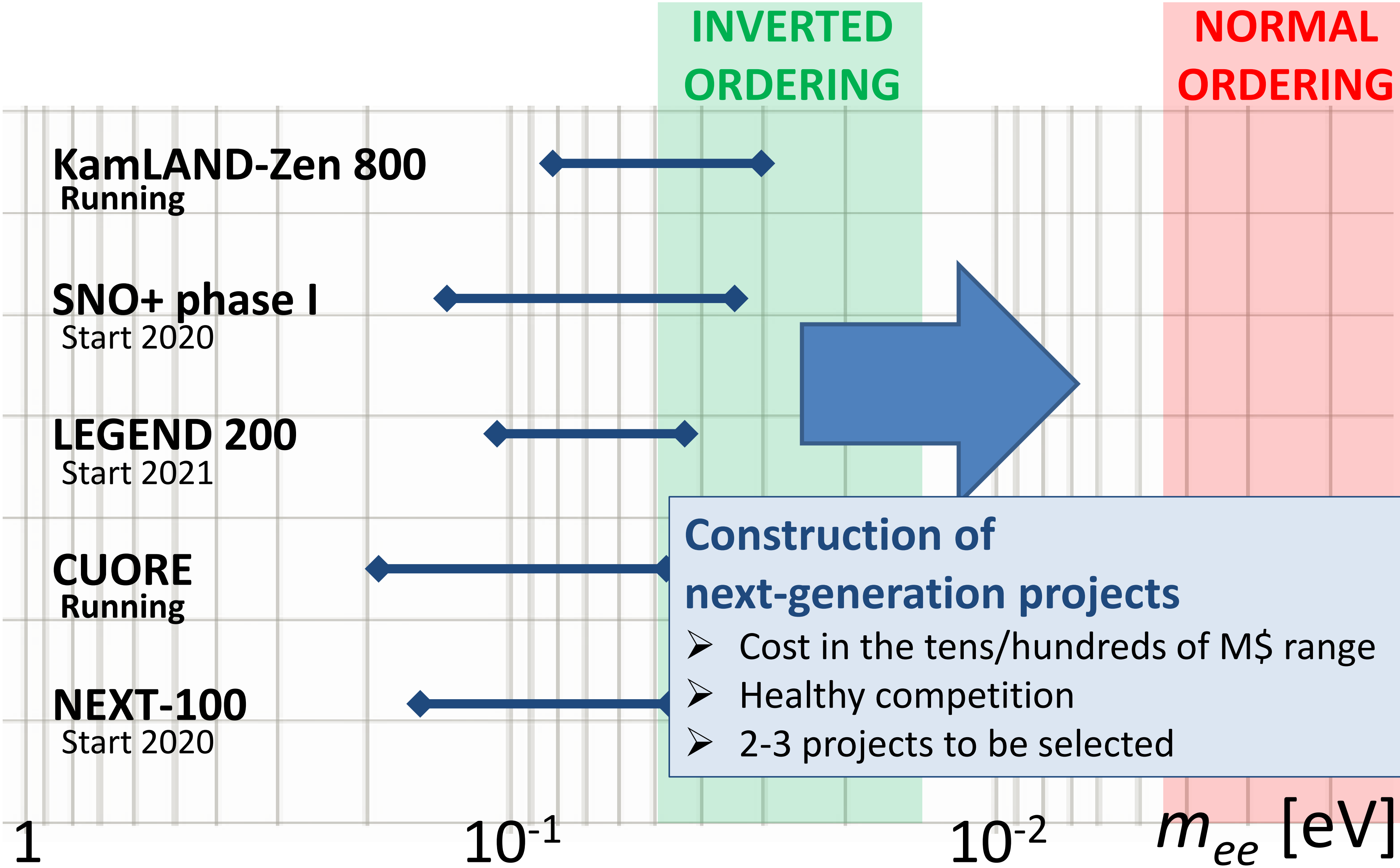
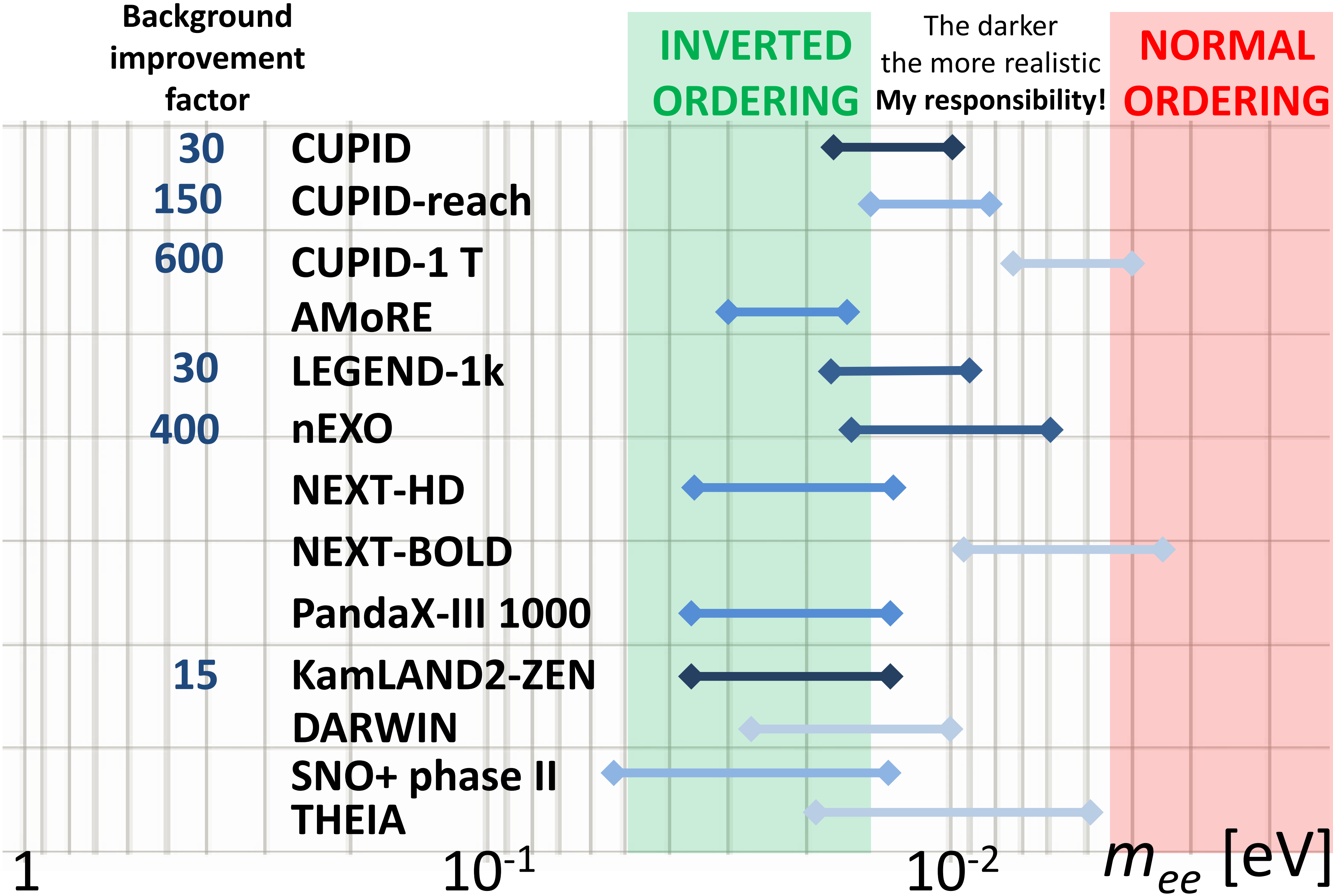



**Construction of next-generation projects**

- Cost in the tens/hundreds of M$ range
- Healthy competition
- 2-3 projects to be selected

# Reach of next-generation experiments



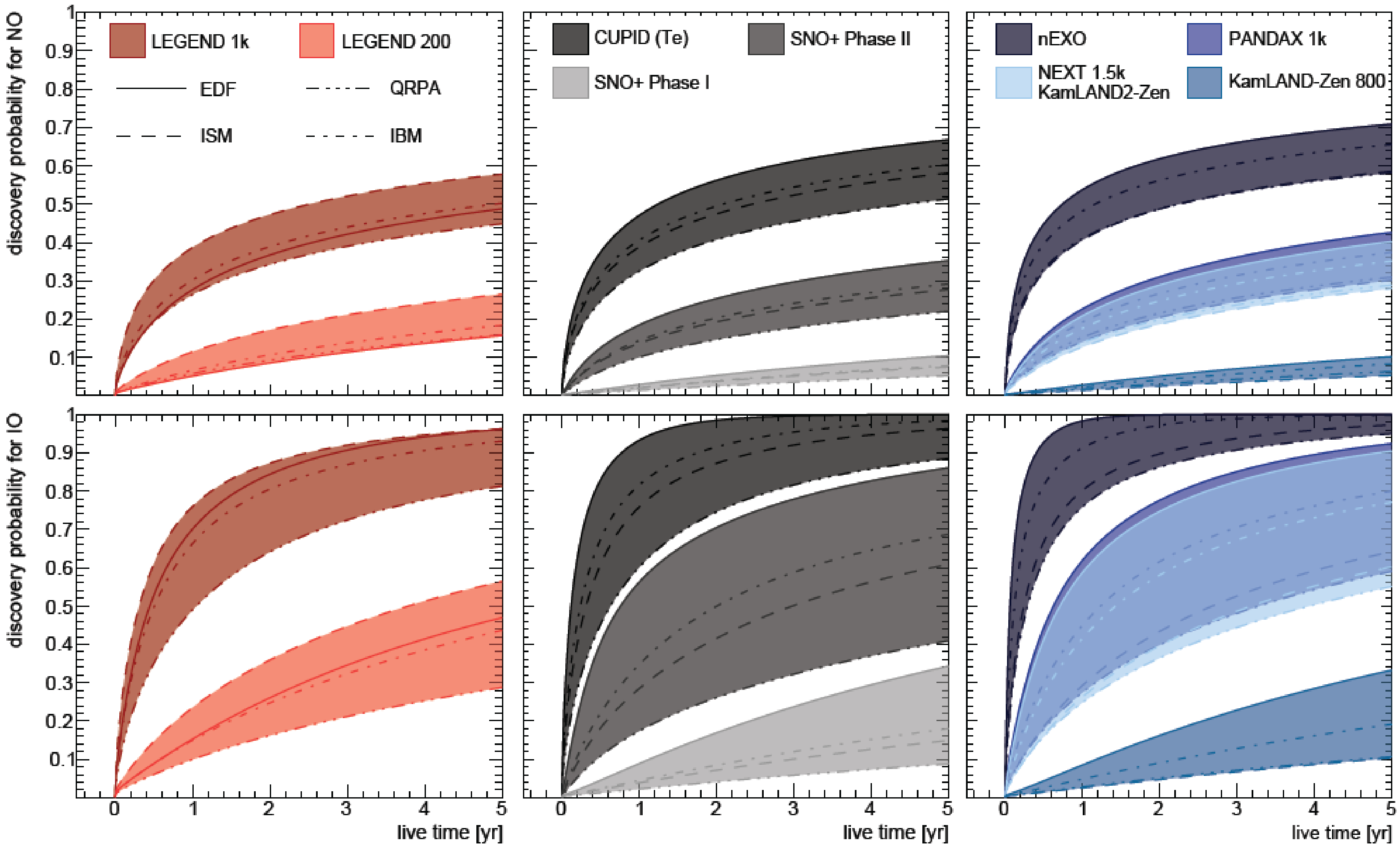
*Phys. Rev. D 96, 053001 (2017)*

# Discovery probability

**Discovery sensitivity**: the value of $T_{1/2}$ or $m_{\beta\beta}$ for which the experiment has a 50% chance to measure a signal with a significance of at least 3 $\sigma$

**Discovery probability**: odds to detect the $0\nu\beta\beta$ signal with significance of at least 3 $\sigma$

→ Obtained by folding the discovery sensitivity with the $m_{ee}$ distribution



# How to reach the few meV scale

**$\geq$ 10 ton isotope** **~ 100 ton × y exposure**

Large dedicated enrichment facility?

Strongly favored isotopes: $^{130}$**Te** – $^{136}$**Xe** (bolometers, TPCs)

Problem with $^{76}$Ge: low Q value, low phase space

Problem with $^{100}$Mo: fast 2$\nu$ double beta decay

**Background < 0.02 counts /(FWHM ton y)**

Factor 10 better than the best ever achieved (GERDA)

Diluted isotopes strongly disfavored by solar neutrinos

→ High dilution factors possible in opaque scintillators? (LiquidO)
Directionality from Cherenkov + scintillation? (THEIA)

**Large-scale bolometric set-up and multiple large Xe TPC are possible** ← Ba tagging

# 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

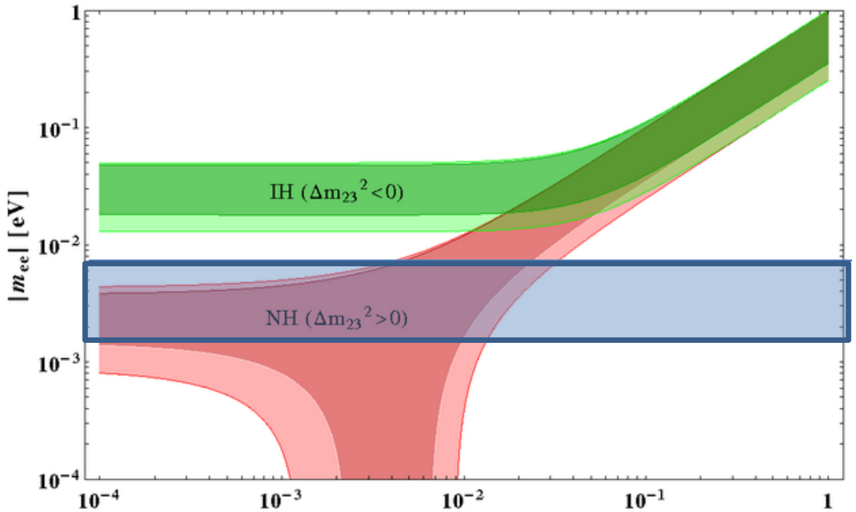
Background index: b = $10^{-5}$ counts/(keV kg y) (testable in CUPID)

Live time: 10 y

**90%** sensitivity:

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

**$m_{ee} < 1.6 – 7.5$ meV**



# 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 field is extremely active: variety of approaches and technologies

*Yesterday's discovery is today's calibration*.

# Conclusions

- $0\nu2\beta$ is a crucial process, not only for neutrino physics
- Next-generation experiments have a good discovery potential
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*Yesterday's discovery is today's calibration.*

*… and tomorrow's background!*