Neutrinoless Double Beta Decay: present and future

Claudia Nones
CEA/IRFU

Ecole de Gif 2022, 5-9 September 2022

Outline

- What is neutrinoless double beta decay
- Why it is important
- How much it is difficult
- Which isotopes and which techniques
- State of the art
- Challenges for the future

Nuclear Double Beta Decay

Double Beta Decay is the **rarest nuclear weak process**

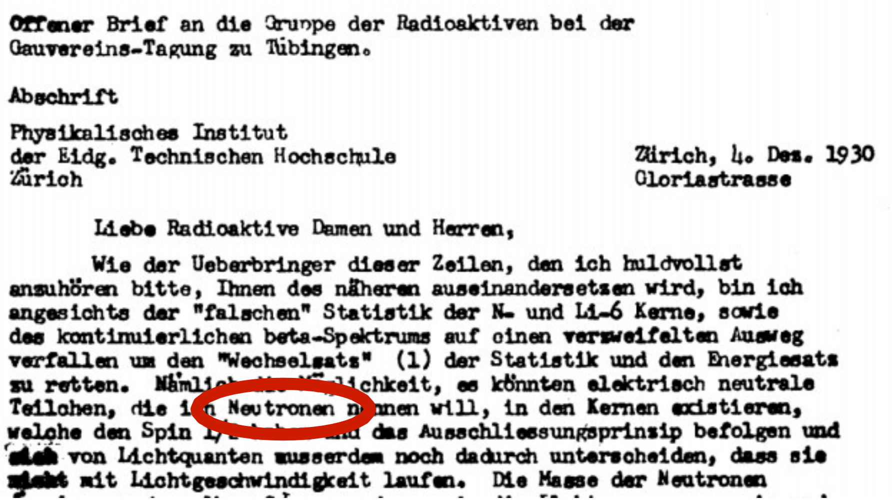
It takes place between **two even-even isobars**

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

Beta decays and new phsyics

Single β decay $(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e$

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

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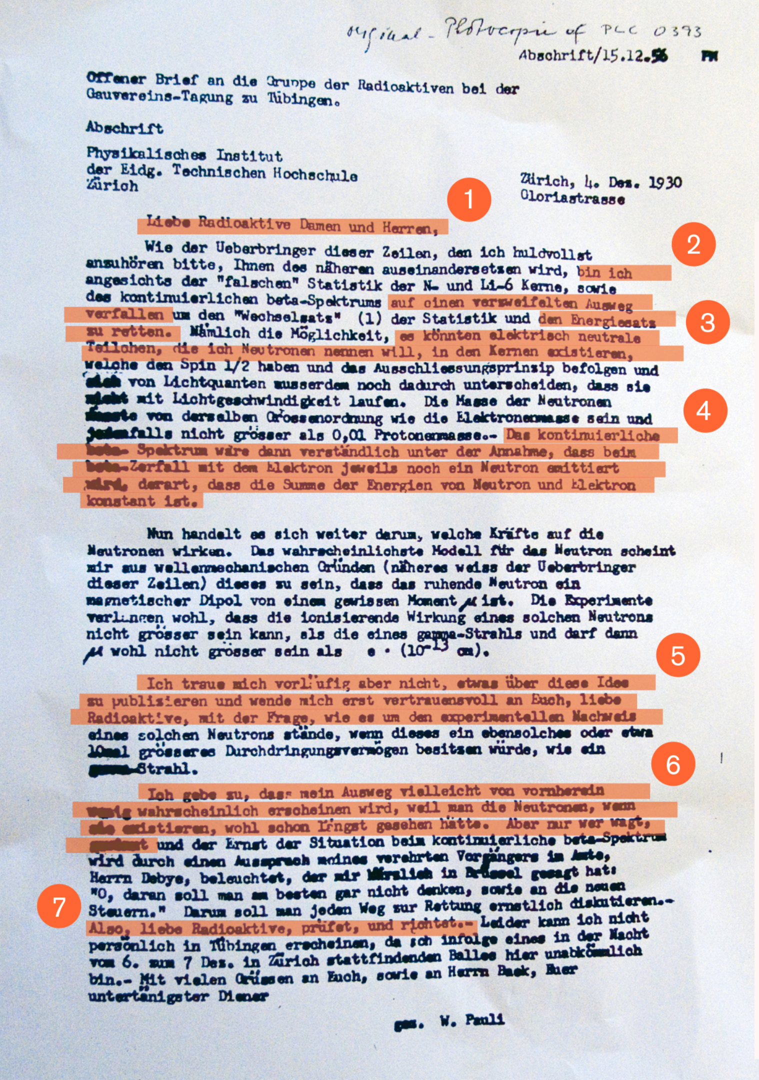

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Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

⑤ Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

⑥ Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- ⑦ Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

1 Dear Radioactive Ladies and Gentlemen!

2 I have hit upon a desperate remedy to save…the law of conservation of energy.

3 …there could exist electrically neutral particles, which I will call neutrons, in the nuclei…

4 The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

5 But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron…

6 I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained…

7 Thus, dear radioactive ones, scrutinize and judge.

Beta decays and new phsyics

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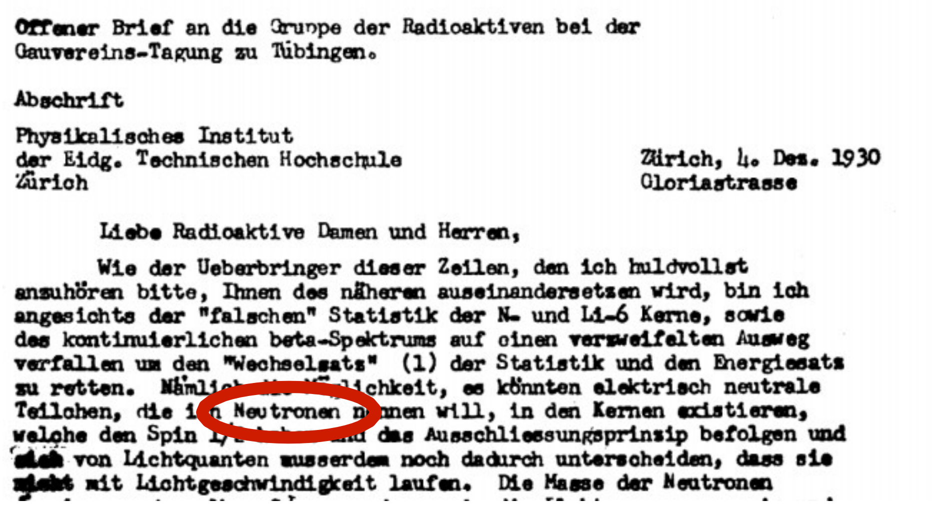

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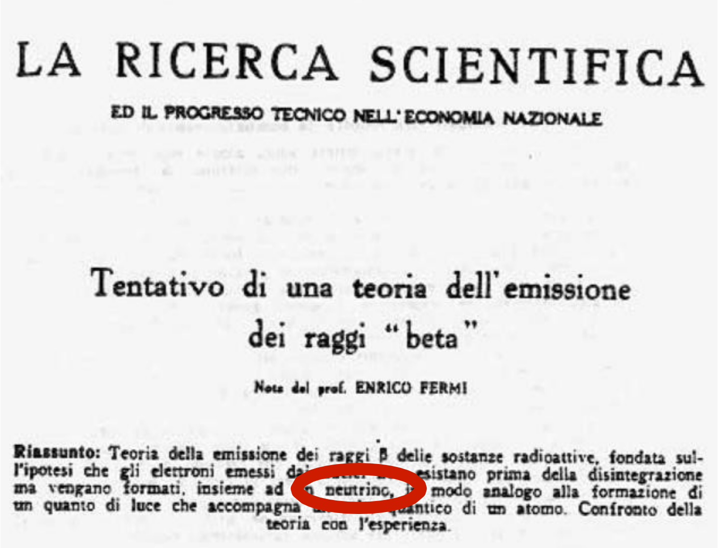
Enrico Fermi,
“Attempt at a beta-ray emission theory”,
(1933)



· 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”

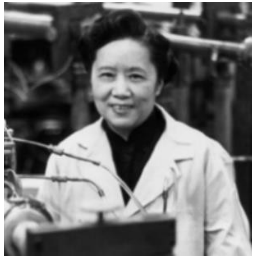
Nota del prof. ENRICO FERMI

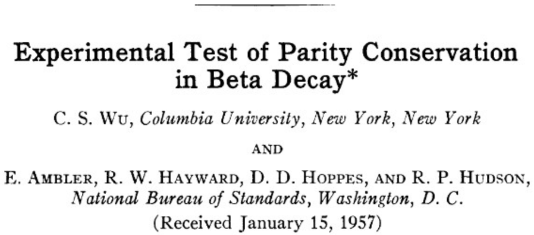
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai [illegible] esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna [illegible] quantico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

Beta decays and new phsyics

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

Chieng-Shiung Wu, Parity Violation (1956)





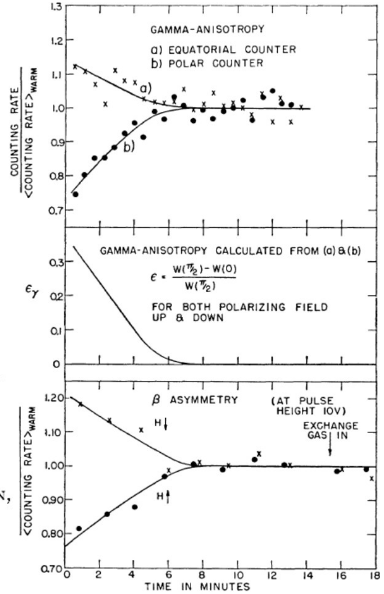
Experimental Test of Parity Conservation in Beta Decay*

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.*

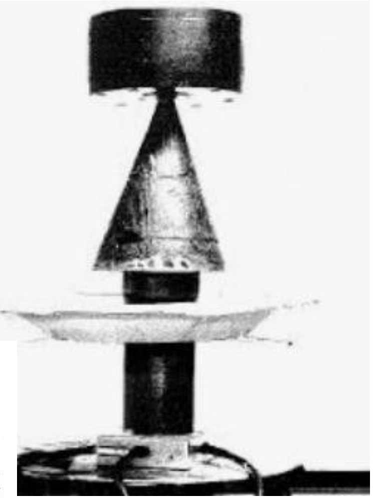
(Received January 15, 1957)

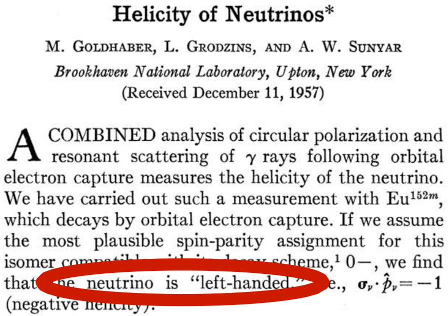


At millikelvin temperatures!

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

Maurice Goldhaber, Helicity of neutrinos (1957)





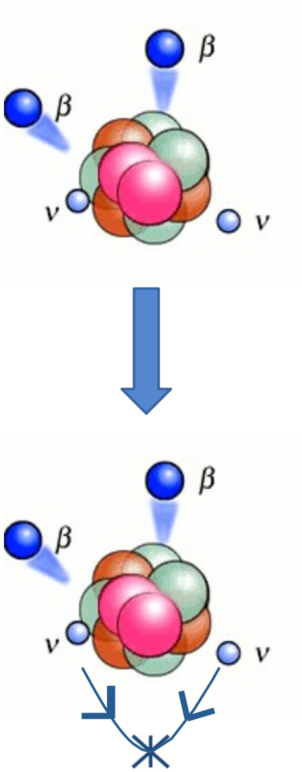
Helicity of Neutrinos*

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., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).

Double Beta decay

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ 2ν2β

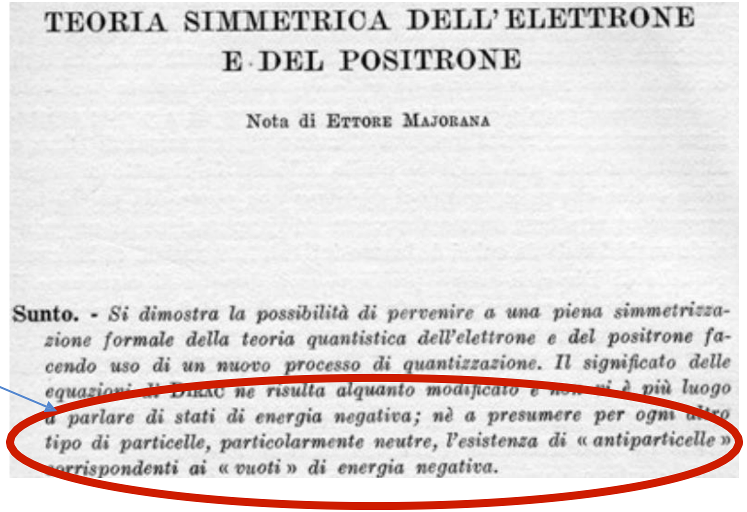


Ettore Majorana

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

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

Nuovo Cimento 14(1937)171-184



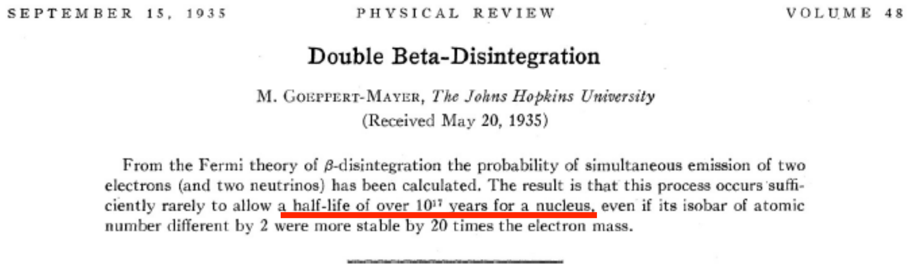
TEORIA SIMMETRICA DELL' ELETTRONE
E DEL POSITRONE

Nota di ETTORE MAJORANA

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

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ 0ν2β

Wikipedia



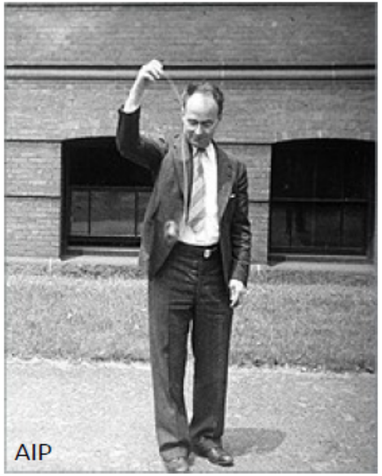
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

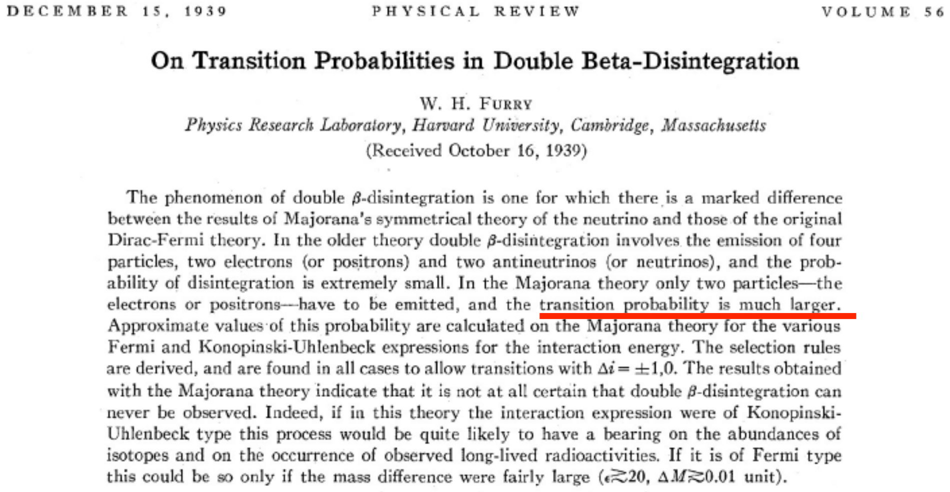
M. GOEPPERT-MAYER, *The Johns Hopkins University*

(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.



AIP



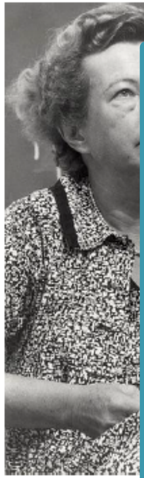
DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

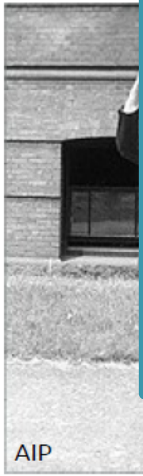
On Transition Probabilities in Double Beta-Disintegration

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. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).





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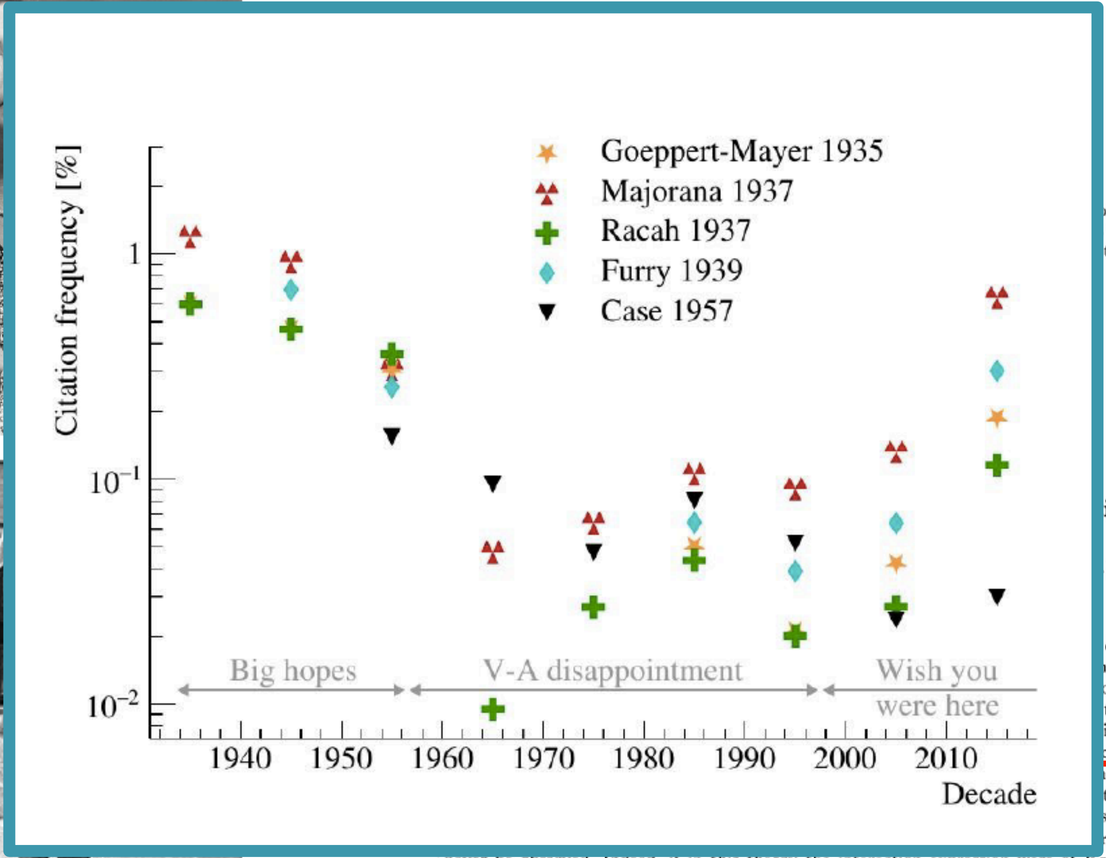

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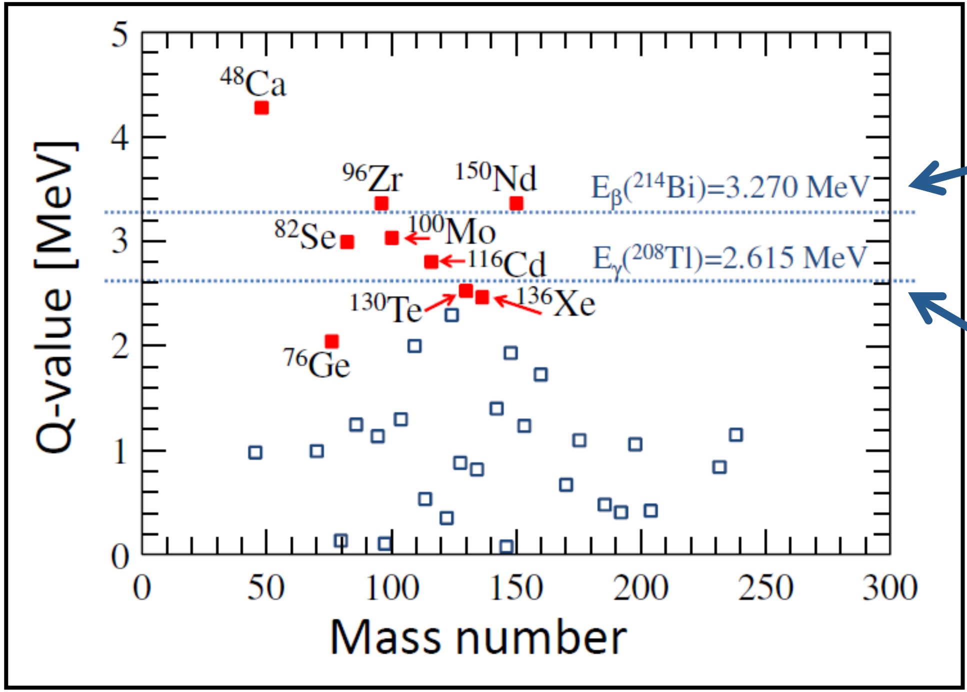
Which and how many nuclei?

Double Beta Decay is the main decay channel for 35 nuclei, with a large span of $\mathbf{Q}_{\beta\beta}$ → energy available for the decay products



Most promising candidates

High $Q_{\beta\beta}$

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

End-point of natural γ radioactivity

Decay channels for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ → 2ν Double Beta Decay
allowed by the Standard Model
already observed – **$\tau \sim 10^{18} - 10^{21}$ y**

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ → **Neutrinoless Double Beta Decay**
never observed
$\tau > 10^{25} - 10^{26}$ y

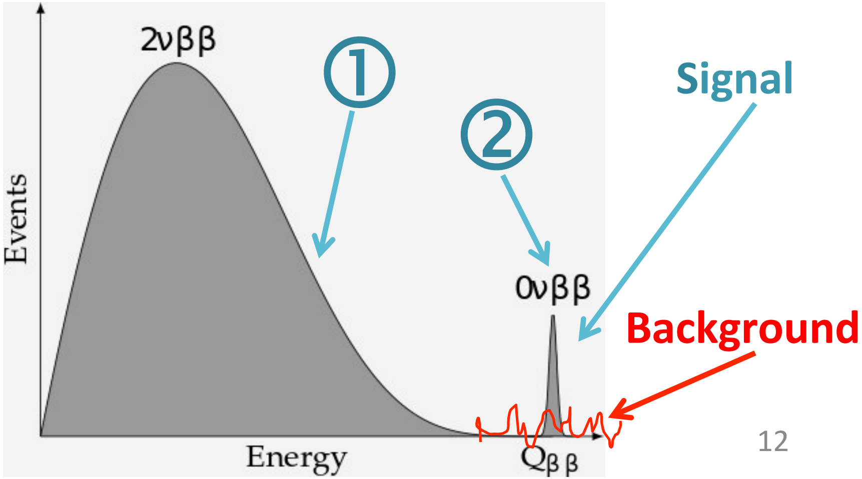
Processes ② would imply **new physics beyond the Standard Model**

violation of total lepton number conservation

Experimental signatures based on the

Sum energy spectrum
of the two electrons

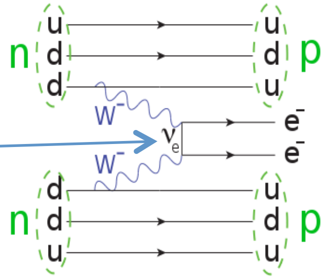
$Q_{\beta\beta}$ ~ 2-3 MeV
for the most promising candidates



Why neutrinoless Double Beta Decay is important

- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism ⇒ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe
- Neutrino mass scale and hierarchy

Standard mechanism: **neutrino physics**
$0\nu2\beta$ is mediated by
light massive Majorana neutrinos
(exactly those which oscillate)
Sometimes defined "**mass mechanism**"



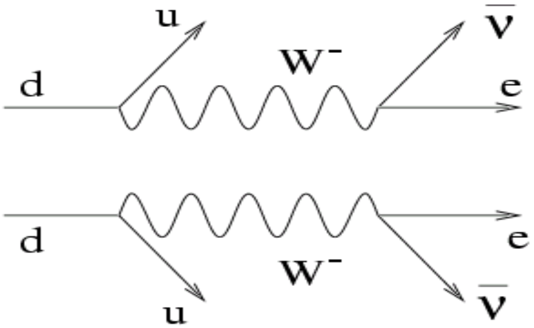
Non-standard mechanisms:
Sterile ν, LNV,…
Not necessarily neutrino physics

- Minimal straightforward extension of the Standard Model
- Metric to compare experiments and technologies

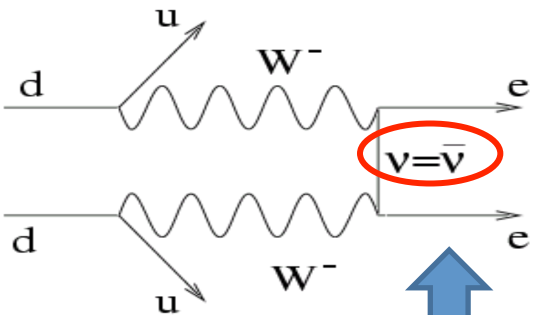
Double beta decay and neutrino physics

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

Diagrams for the two processes discussed above:

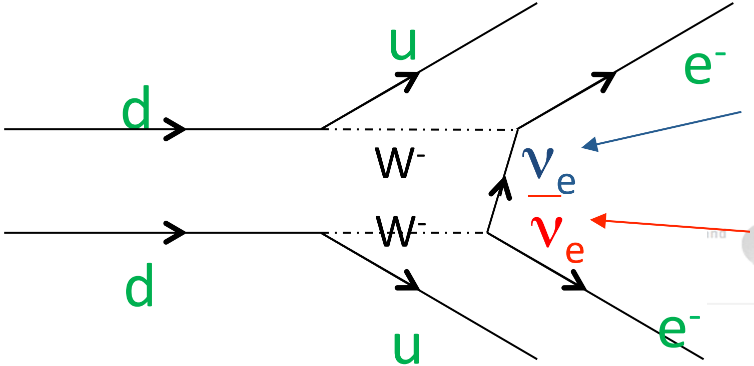


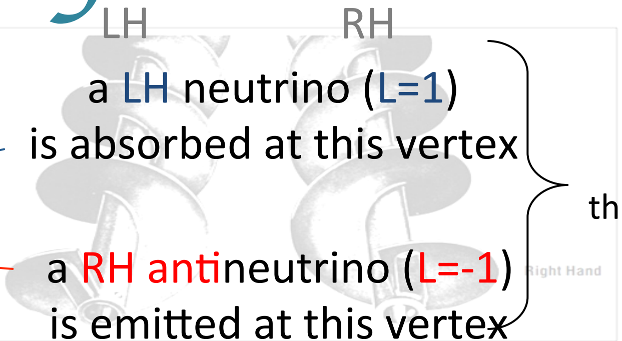
Standard-Model allowed process
two "simultaneous" beta decays



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

Double beta decay and neutrino physics





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

a RH antineutrino (L=-1)
is emitted at this vertex

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

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

- IF neutrinos are massive DIRAC particles:
  Helicities can be accommodated thanks to the **finite mass**,
  BUT Lepton number is rigorously conserved

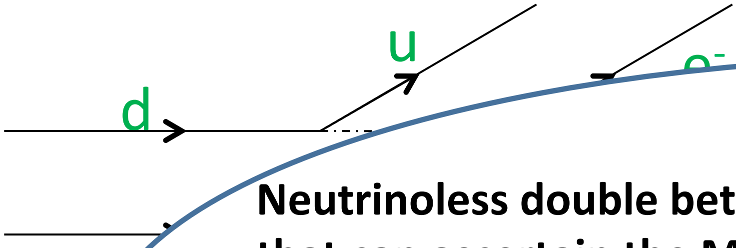
0ν-DBD is forbidden

$\bar{\nu} = \nu$

- 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



a LH neutrino (L=1)

in pre-oscillations
standard particle physics
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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

- IF neutr
  Helicities ca
  BUT Lepton number is rig

DBD
is forbidden

$\nu = \nu$

- IF neutrinos are massive MAJORANA particles:
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0ν-DBD
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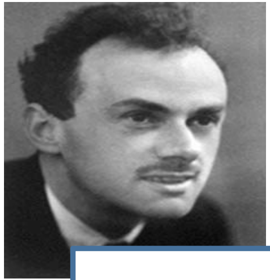
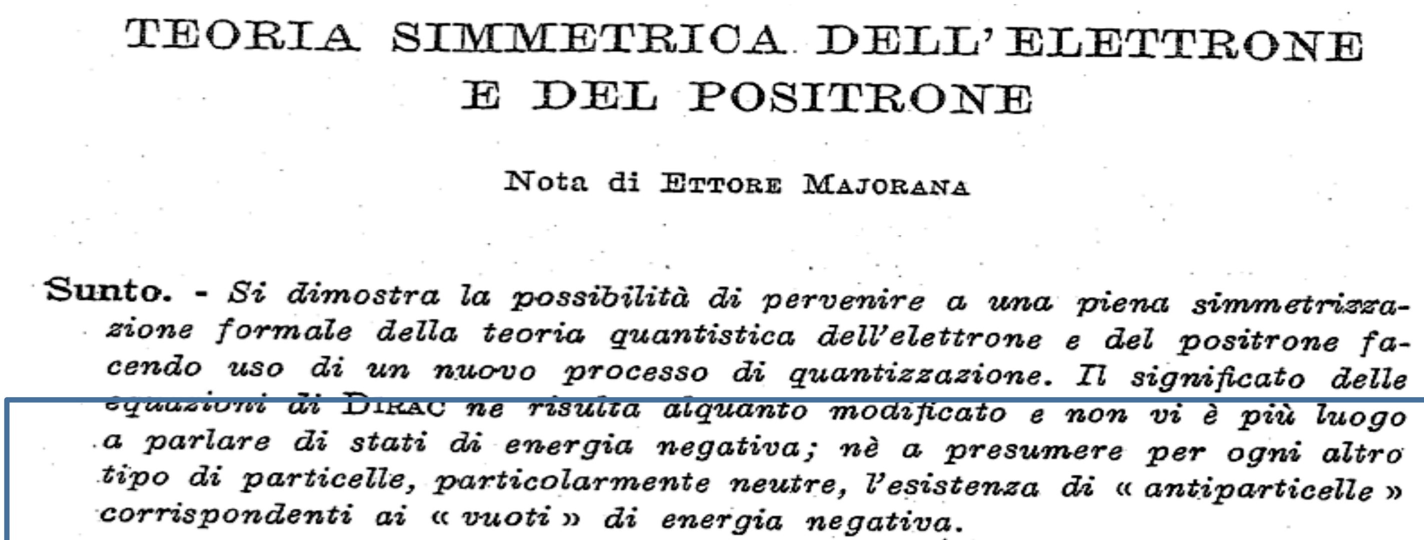
DIRAC or MAJORANA
nature of neutrinos



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

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

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



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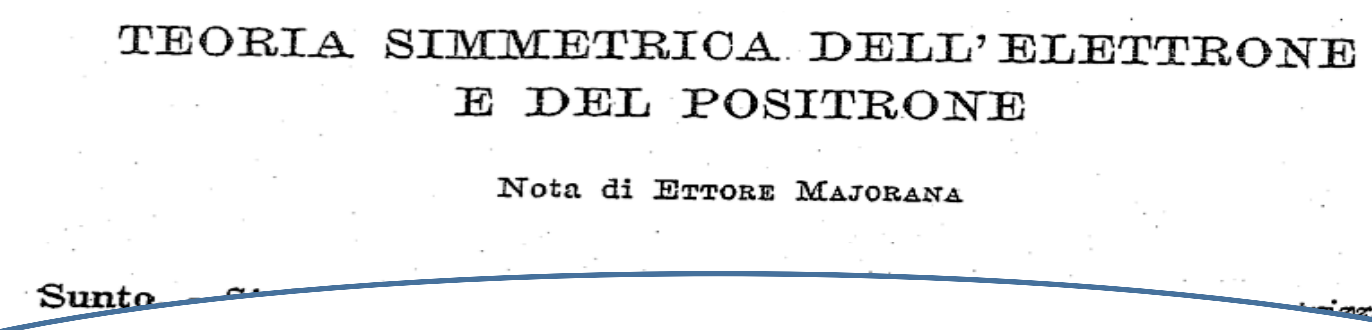
DIRAC or MAJORANA

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**"*).

Rate in case of mass mechanism

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**

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

what the experimentalists try to measure

what the nuclear theorists try to calculate

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

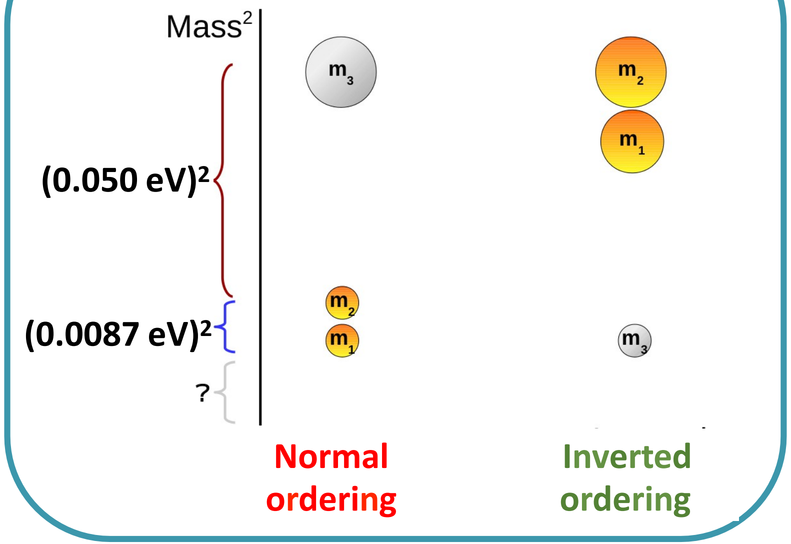
Majorana phases

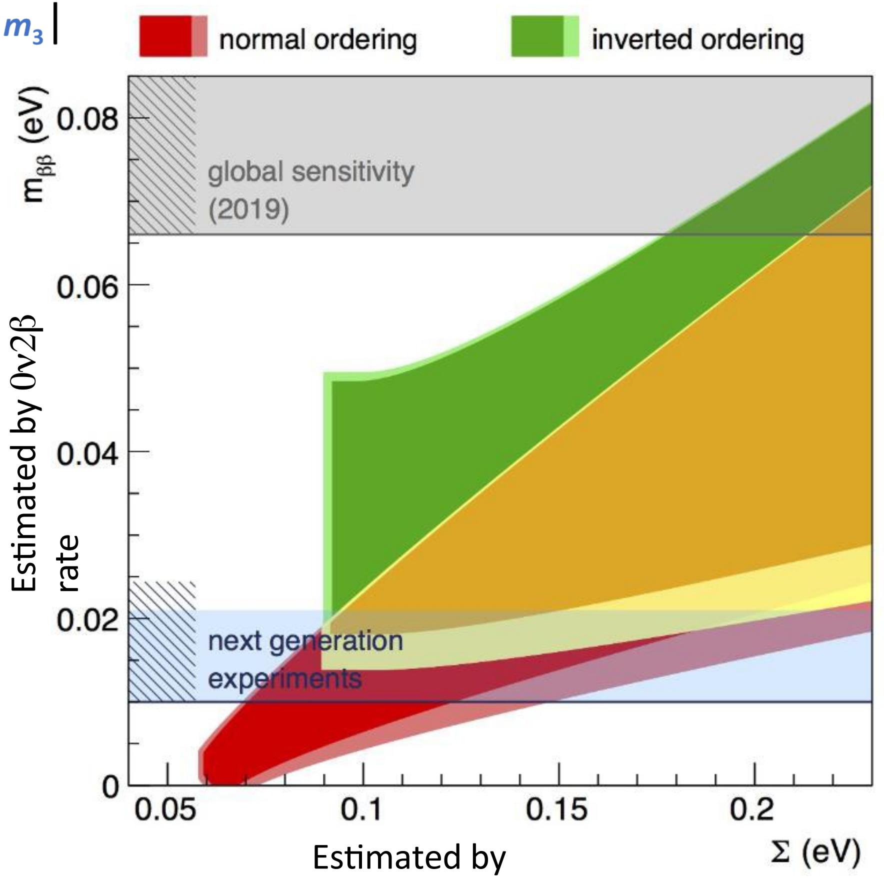
$$\langle \mathbf{M}_{\beta\beta}\rangle = \left|\, |U_{e1}|^{2} M_1 + e^{i\alpha_1} |U_{e2}|^{2} M_2 + e^{i\alpha_2} |U_{e3}|^{2} M_3 \,\right|$$

Light Majorana neutrino exchange

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

From ν oscillation experiments



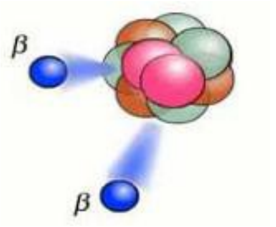


Estimated by cosmology

$= m_1 + m_2 + m_3$

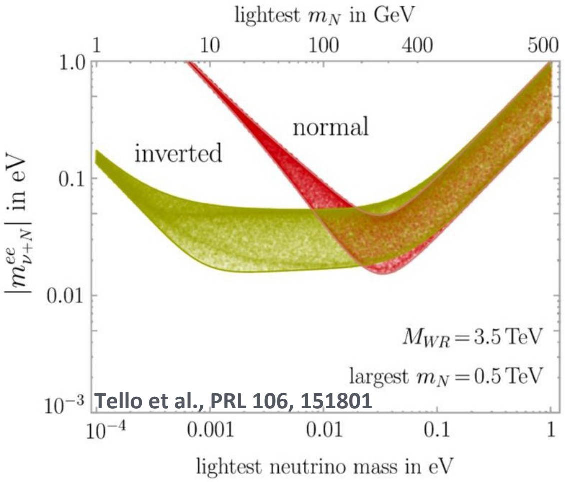
0ν2β : other mechanisms

0ν2β is an inclusive test for the « creation of leptons »:
$2n \rightarrow 2p + 2e^-$ ⇒ **LNV (Letpon Number Violation)**



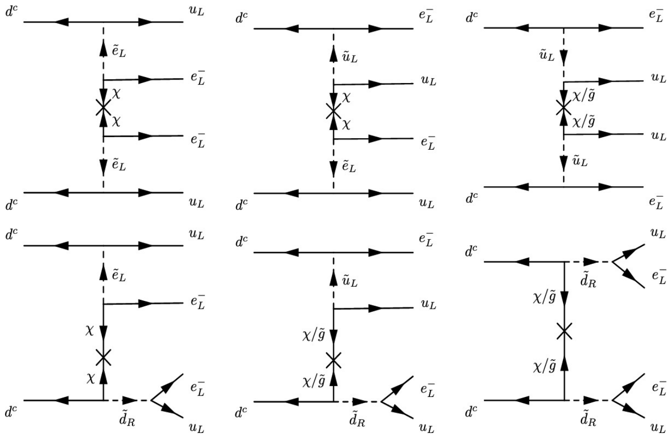
This test is implemented in the nuclear matter: **$(A,Z) \rightarrow (A,Z+2) + 2e^-$**

Left - Right symmetric models



Tello et al., PRL 106, 151801

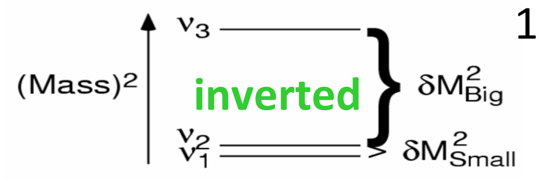
R-Parity violating SUSY models

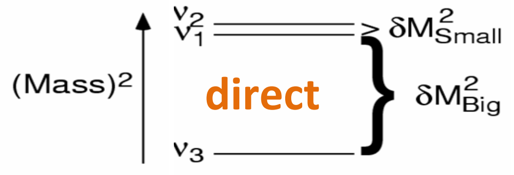


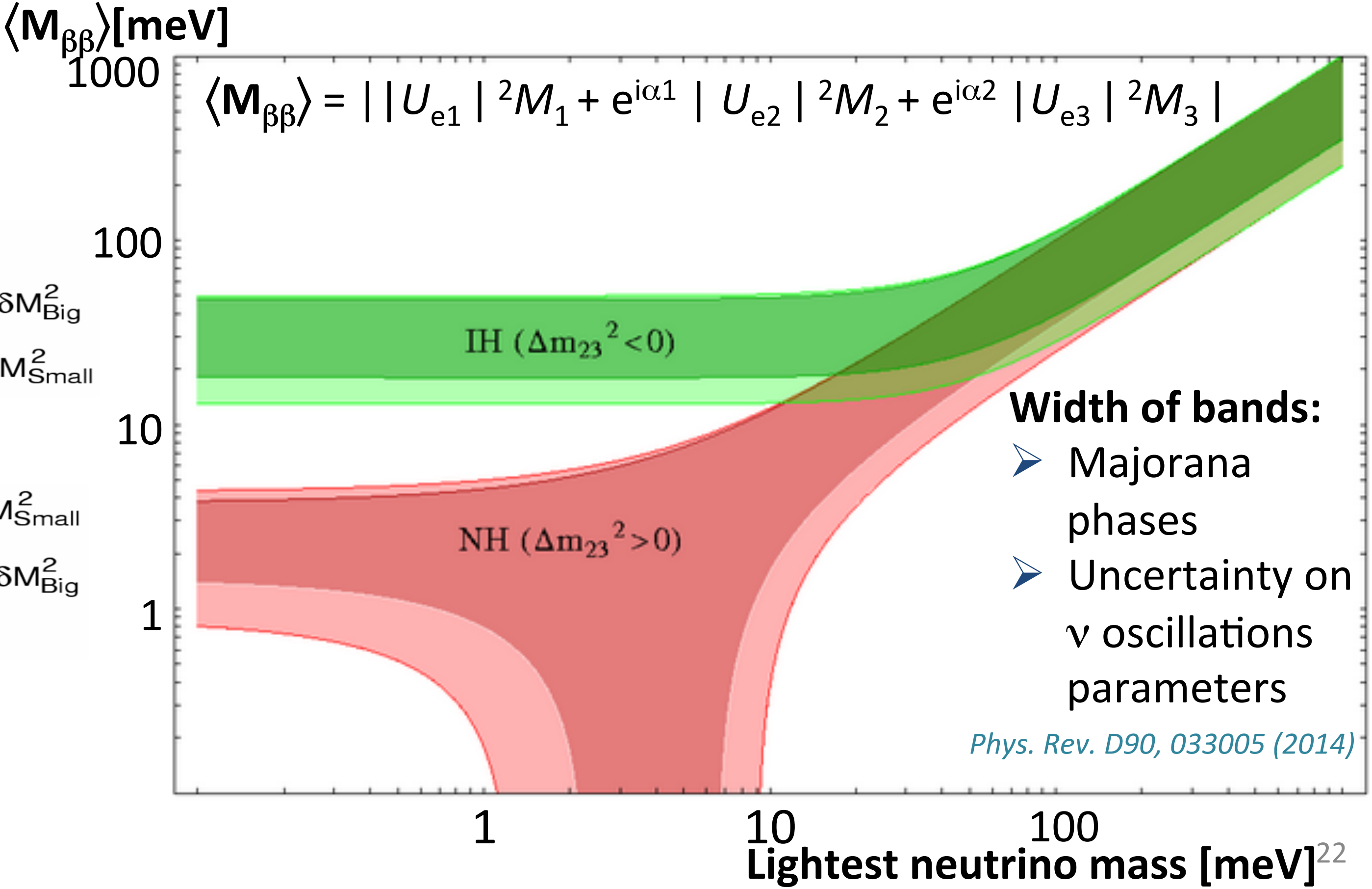
W. Rodejohann et al., Int. J. Mod. Phys E 20, 09, 1833

The effective Majorana mass

A reference plot







$$\langle M_{\beta\beta}\rangle = \left|\,|U_{e1}|^2 M_1 + e^{i\alpha 1}\,|U_{e2}|^2 M_2 + e^{i\alpha 2}\,|U_{e3}|^2 M_3\,\right|$$

Width of bands:

- Majorana phases
- Uncertainty on ν oscillations parameters

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

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

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

Severe reduction of the rate

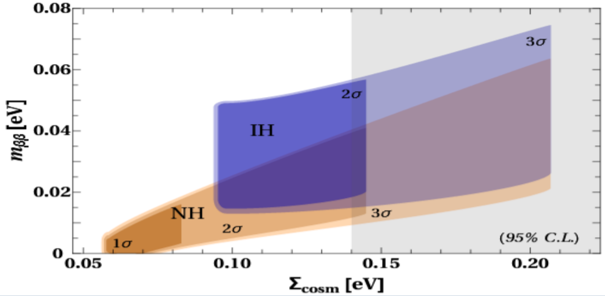
However, **it is not clear if observed quenching can be generalised to $0\nu2\beta$**

Ab initio calculation of M_{nucl} can improve dramatically our understanding of this effect

Constraints from cosmology on **$\Sigma = m_1 + m_2 + m_3$**

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

Model-dependent constraint



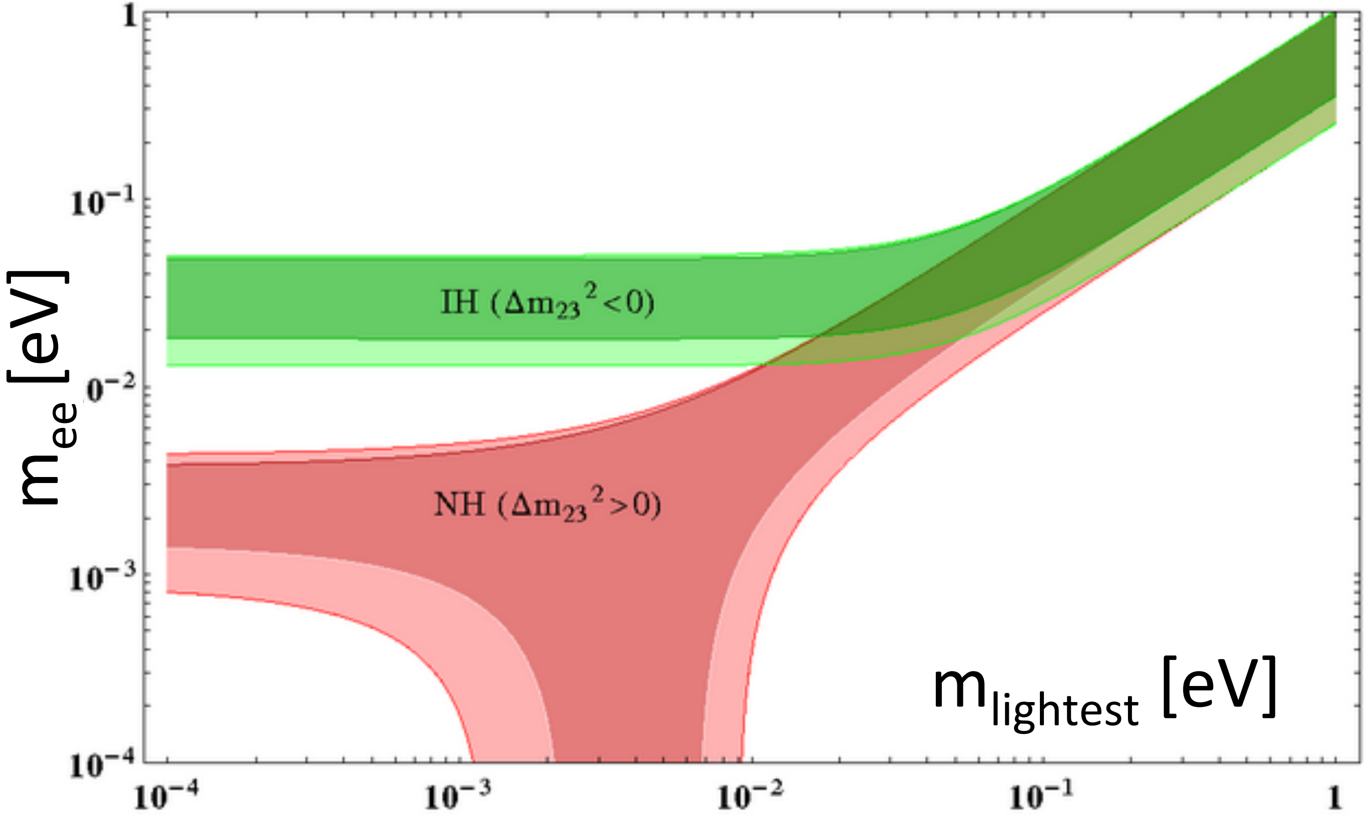
Indication in favor of **Normal Ordering**

Neutrino oscillation in terrestrial matter

Results from **NOvA**, **T2K**, **MINOS**

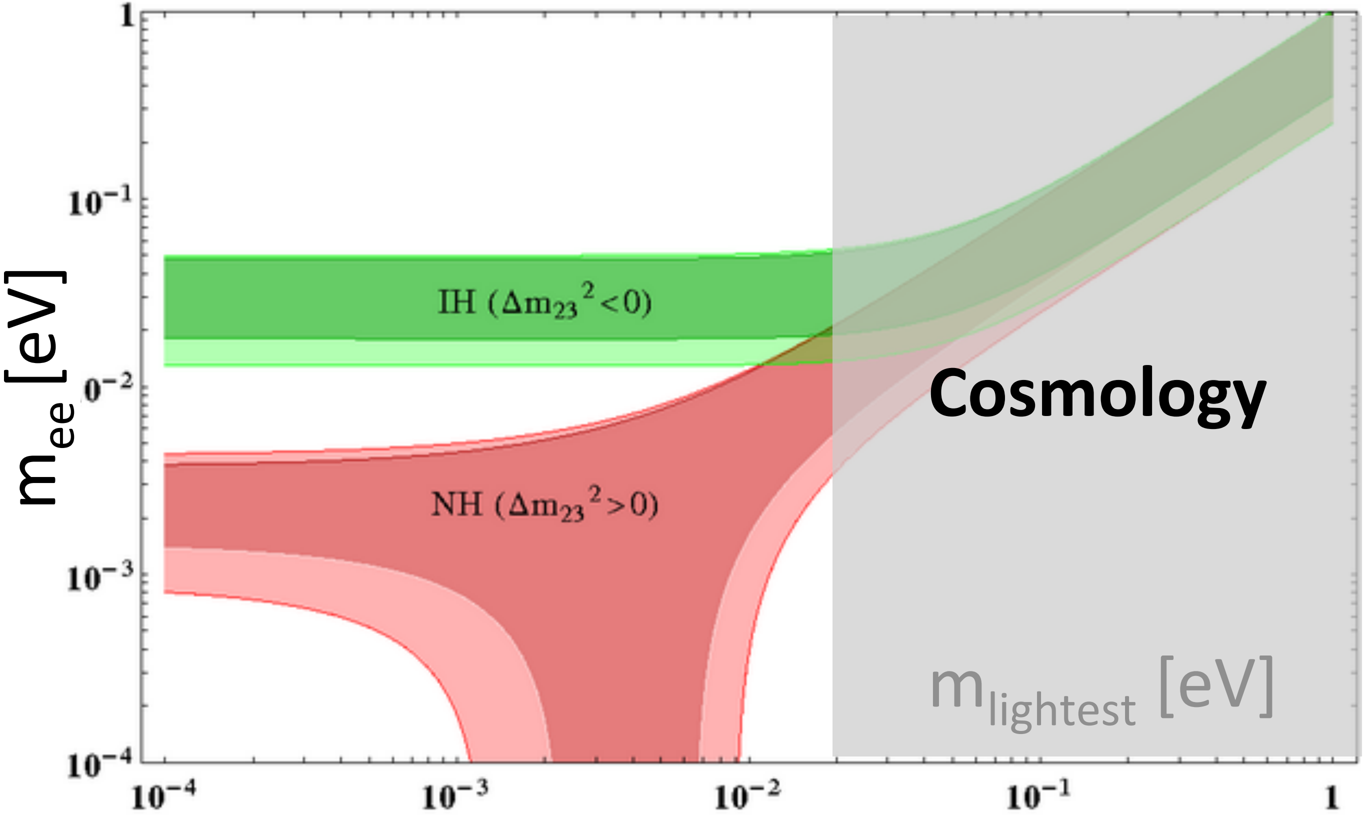
Global analysis

Challenges



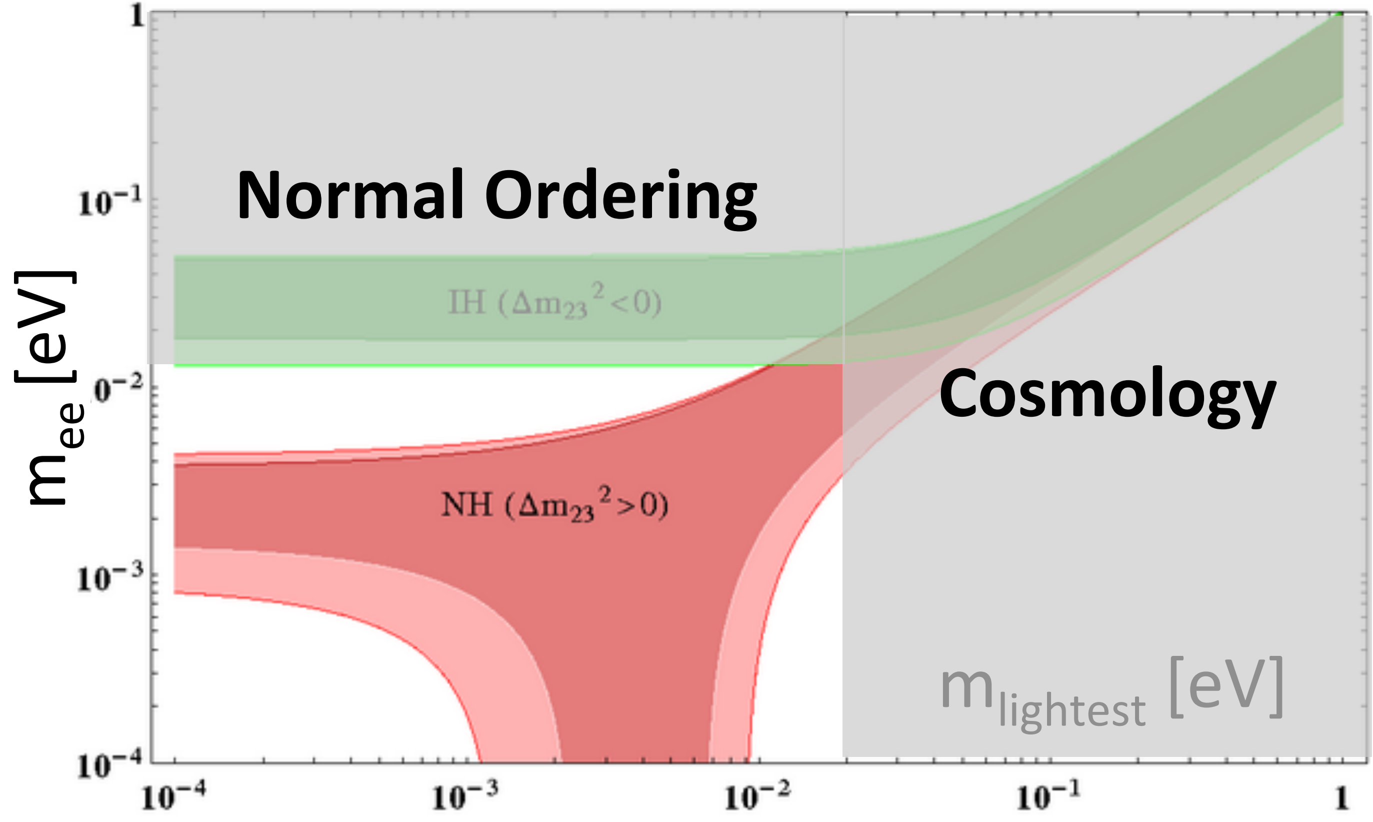
S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)

Challenges



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

Challenges



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

m_{ee} distribution in the parameter space

Phys. Rev. D 96, 053001 (2017)

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

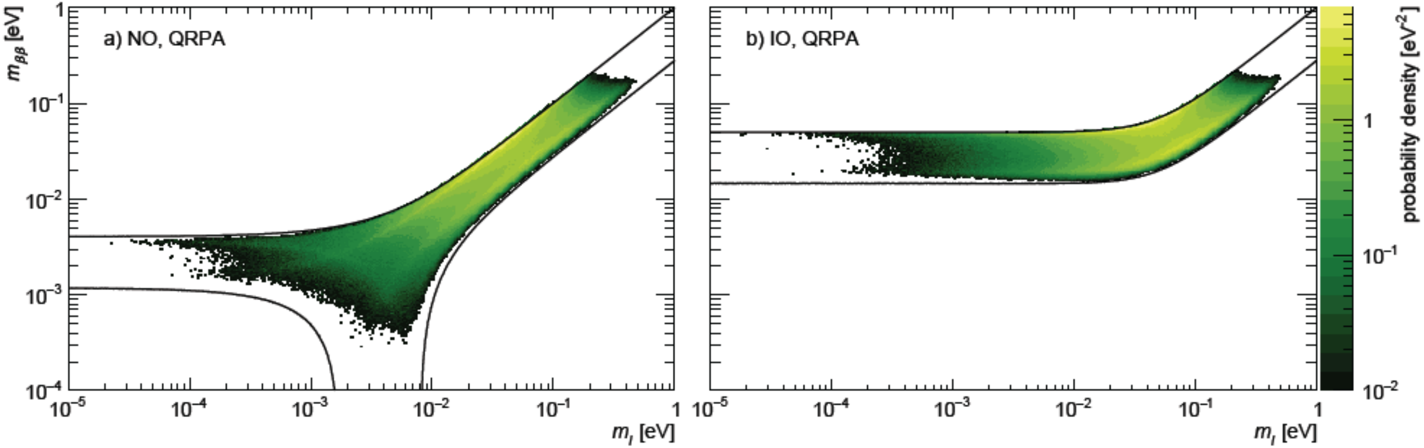
Discovery probability of next-generation neutrinoless double-β decay experiments

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

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

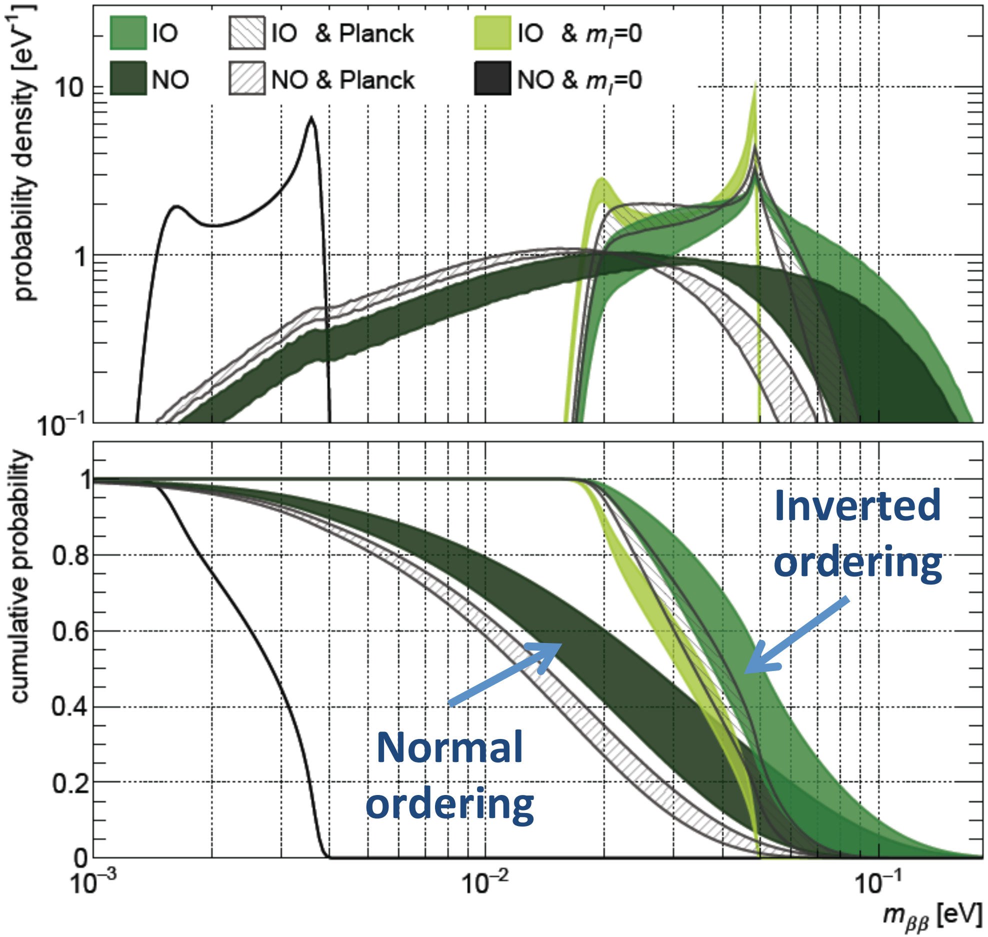
- $\Sigma = m_1+m_2+m_3$, Δm_{ij}^2: **logarithmic**
- Angles and phases in PMNS matrix: **flat**

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



Phys. Rev. D 96, 053001 (2017)

Probability densities and cumulative probabilities for m_{ee}



Inverted ordering

Normal ordering

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.

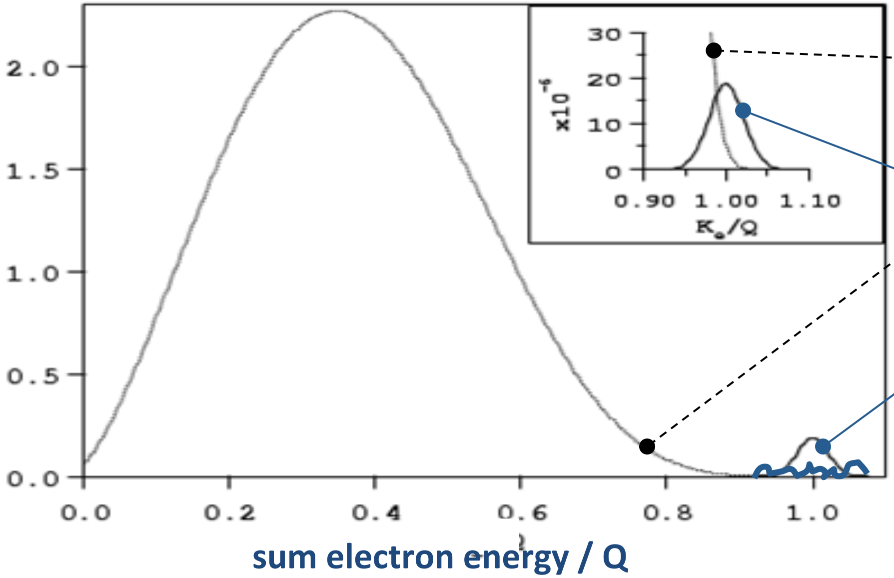
g_A quenching has an important effect but not dramatic

30% g_A quenching reduces the discover potential by

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

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

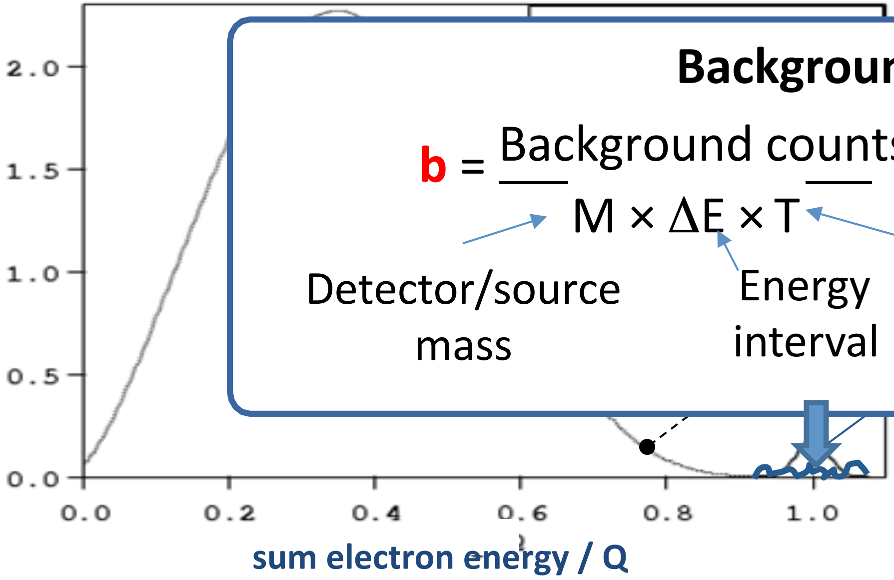
0ν2β : (A,Z)→(A,Z+2)+2e
peak enlarged only by
the detector energy resolution

Q ~ 2-3 MeV for the most
promising candidates

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

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



Background index

$$\mathbf{b} = \frac{\text{Background counts}}{M \times \Delta E \times T} \quad [\text{counts}/(\text{keV kg y})]$$

Detector/source mass

Energy interval

Measurement time

→(A,Z+2)+2e+2ν

maximum at ~1/3 Q

)→(A,Z+2)+2e

rged only by

energy resolution

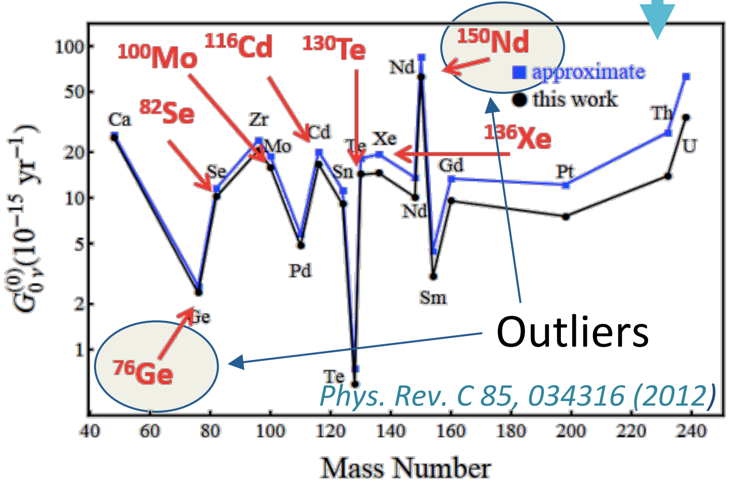
Q ~ 2-3 MeV for the most promising candidates

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

Nuclear physics

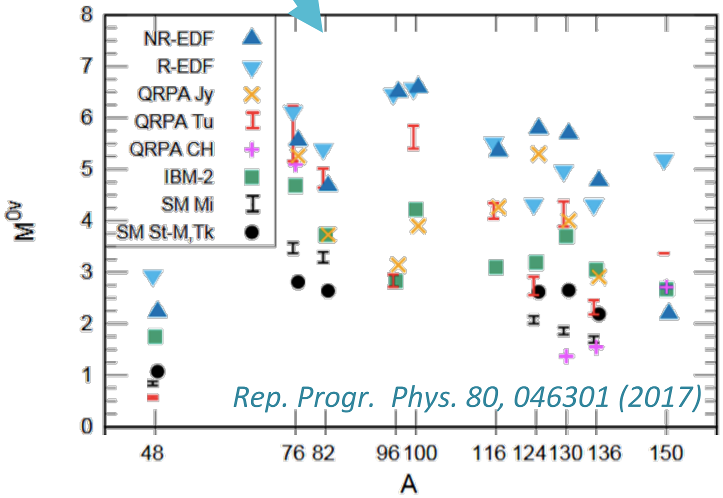
$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$

Phase space: exactly calculable



Outliers

Phys. Rev. C 85, 034316 (2012)



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

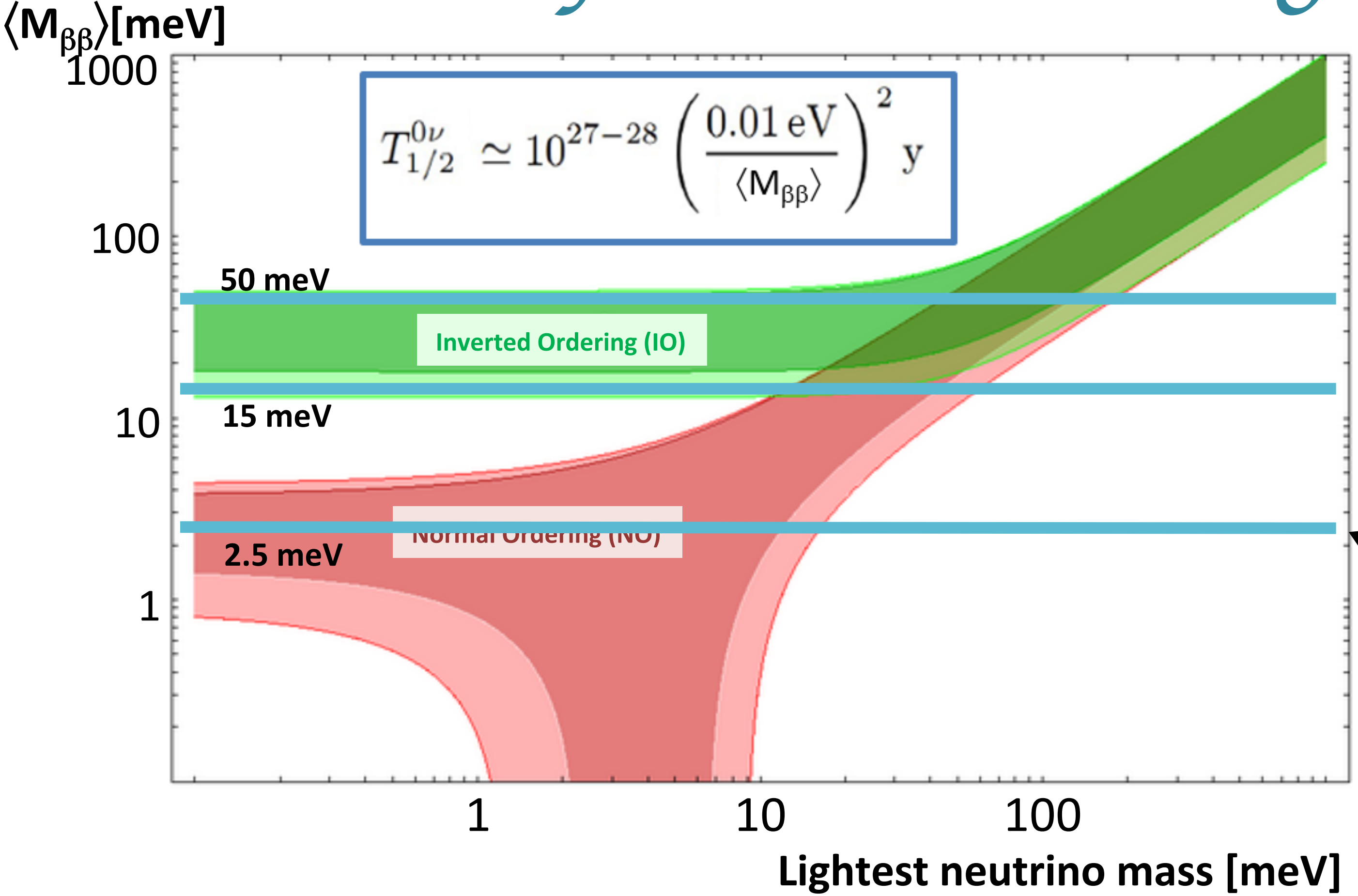
The $0\nu\beta\beta$ community still assumes **$g_A \approx 1.27$** (no quenching)

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

- Typically, a factor ~3 of spread for **$|M_{nucl}|$**
- **A spread of ~10 is expected in the rate predictions**
- Again **a factor ~3 of spread** is expected for **$\langle M_{\beta\beta}\rangle$**

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

Experimental challenge



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

$T^{0\nu}_{1/2} \sim 10^{26}$ y

~ **10 counts / (tonne y)**

Reach of the **current** searches

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

~ **10 counts / (tonne 10y)**

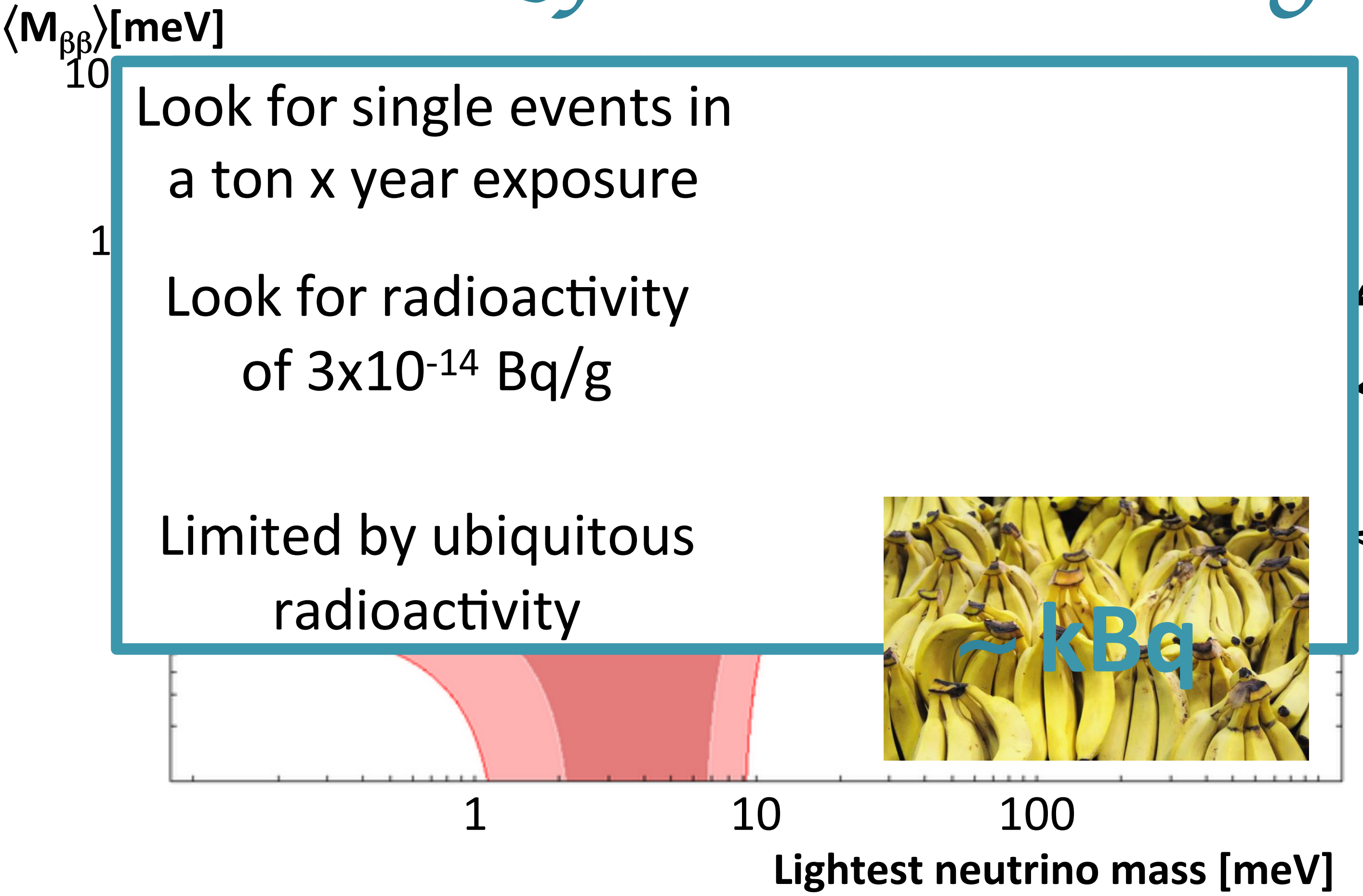
Reach of **next-generation** searches

$T^{0\nu}_{1/2} \sim 10^{29}$ y

~ **0.1 counts / (tonne 10y)**

Next-to-next generation

Experimental challenge



Look for single events in a ton x year exposure

Look for radioactivity of 3×10^{-14} Bq/g

Limited by ubiquitous radioactivity

$T^{0\nu}_{1/2} \sim 10^{26}$ y

~ 10 counts / (tonne y)

Reach of the **current** searches

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

~ 10 counts / (tonne 10y)

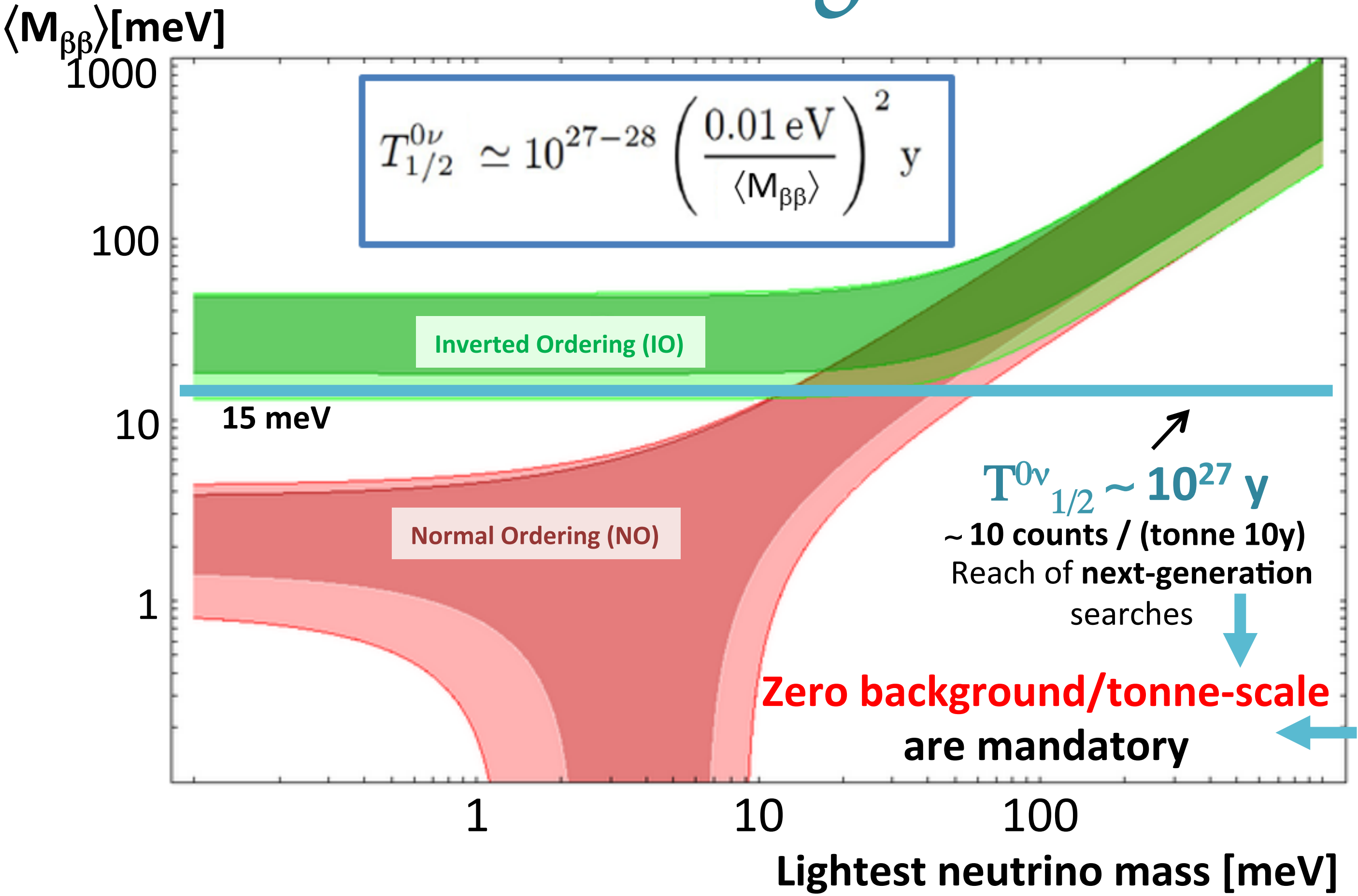
Reach of **next-generation** searches

$T^{0\nu}_{1/2} \sim 10^{29}$ y

~ 0.1 counts / (tonne 10y)

Next-to-next generation

Next generation



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

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

~ 10 counts / (tonne 10y)

Reach of **next-generation** searches

Zero background/tonne-scale

are mandatory

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

$$\frac{\textbf{background counts @}Q_{\beta\beta}}{M \times \Delta E \times T}$$

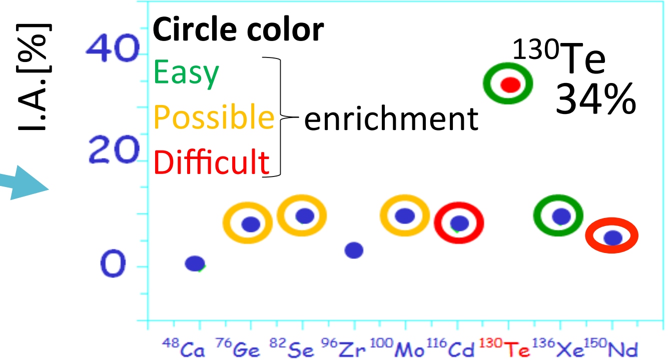
Zero background

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

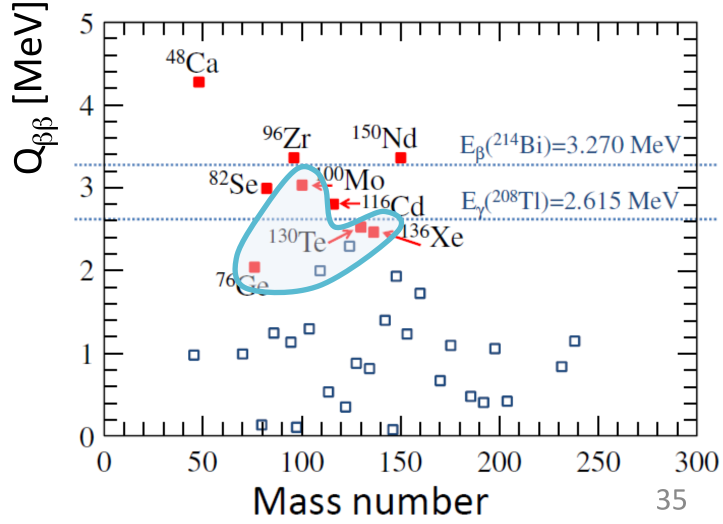
$$F \propto MT$$

Factors guiding isotope selection

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

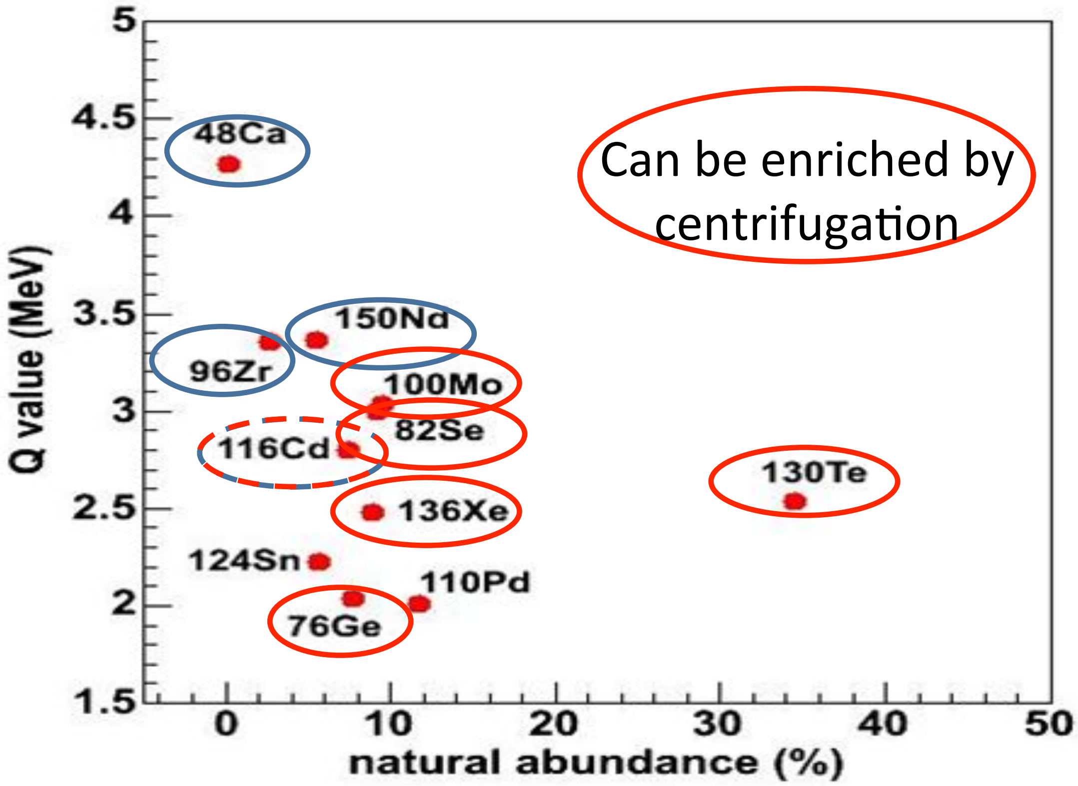


- **High $Q_{\beta\beta}$**
  - Larger phase space: $G(Q,Z) \propto Q^5$
  - Easier background control

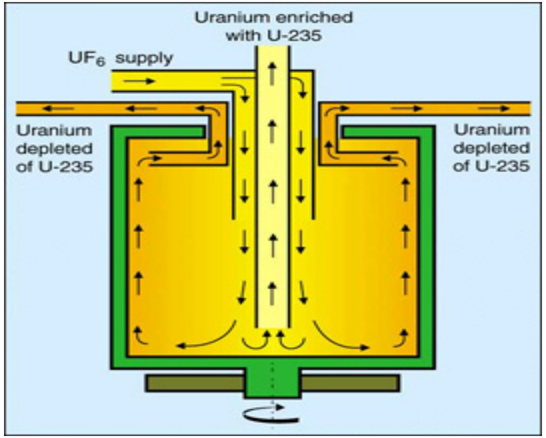


- Compatibility with a beneficial detection technique
  - **High energy resolution**
  - **Background identification**
  - **Efficiency and scalability**

Isotopic abundance



Can be enriched by centrifugation

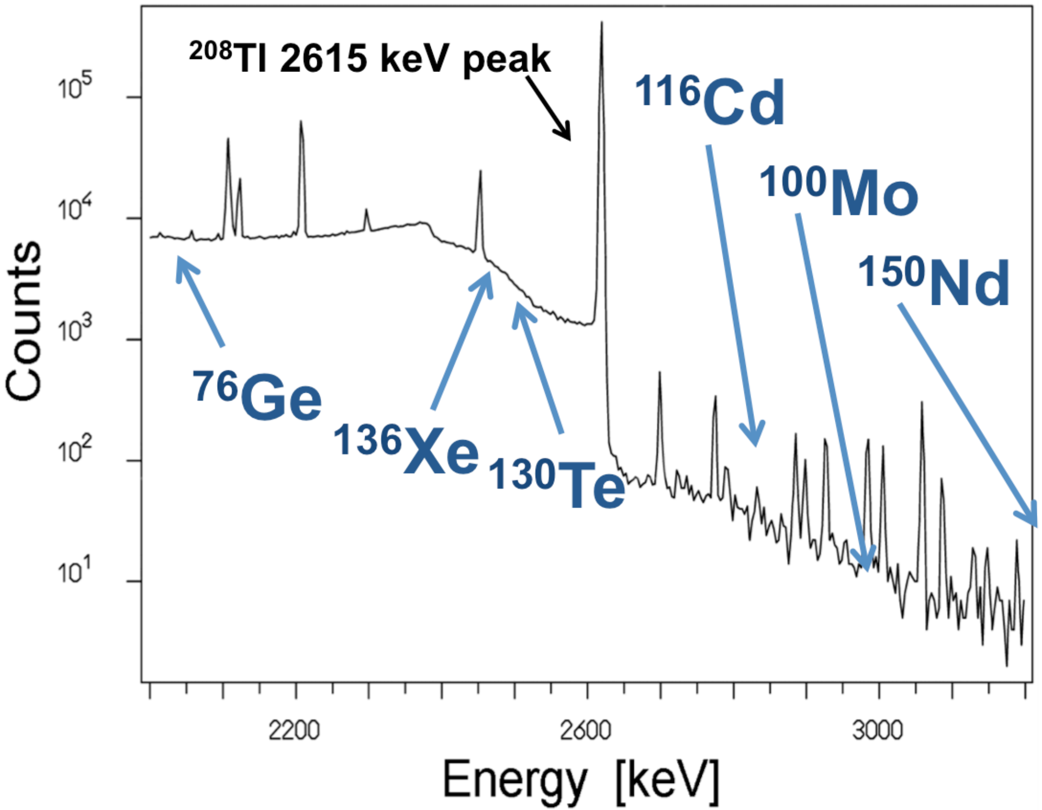


Isotopic enrichment by **centrifugation** – Currently, the only viable large-scale method

Almost, **Russian monopoly**
Cost: 10-80 €/g
1 ton: 10 – 80 M€

Q value and gamma background

Isotope	Daughter	$Q_{\beta\beta}$[a] [keV]
^{48}Ca	^{48}Ti	4 267.98(32)
^{76}Ge	^{76}Se	2 039.061(7)
^{82}Se	^{82}Kr	2 997.9(3)
^{96}Zr	^{96}Mo	3 356.097(86)
^{100}Mo	^{100}Ru	3 034.40(17)
^{116}Cd	^{116}Sn	2 813.50(13)
^{130}Te	^{130}Xe	2 527.518(13)
^{136}Xe	^{136}Ba	2 457.83(37)
^{150}Nd	^{150}Sm	3 371.38(20)

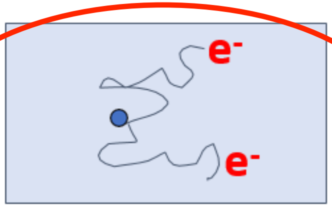


General features for 0ν2β searches

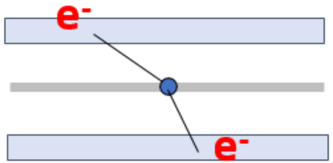
Requests for the source

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 0ν2β

Requests for the background

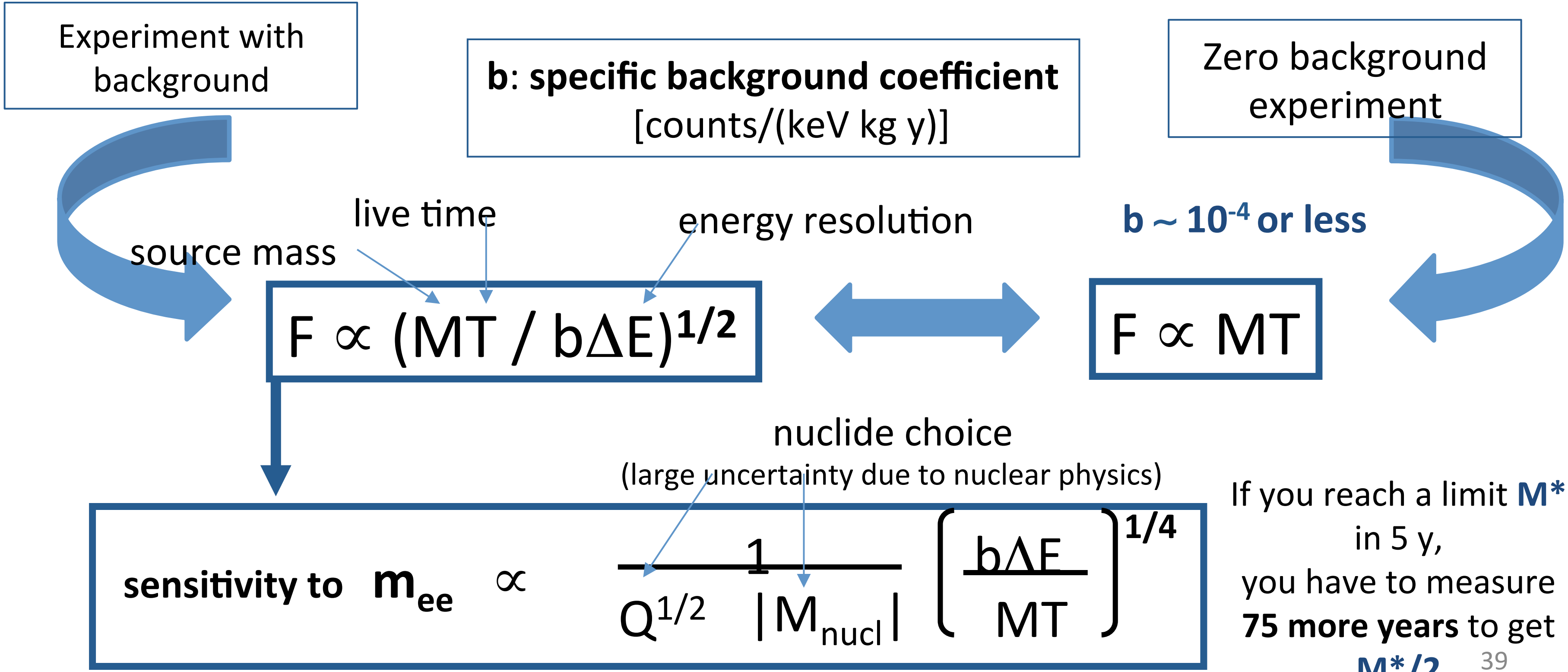
Generic measures as underground operation, shielding (passive and active), radiopurity of materials, vetos are common to 0ν2β and other rare event search

Specific desirable features for 0ν2β

- 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

The sensitivity

sensitivity F: lifetime corresponding to the minimum excluded number of signal events (for a given confidence / credibility interval)



Experiment with background

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

Zero background experiment

live time

source mass

energy resolution

$b \sim 10^{-4}$ or less

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

$$F \propto MT$$

nuclide choice

(large uncertainty due to nuclear physics)

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

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

The sensitivity

sensitivity F: lifetime corresponding to the minimum excluded number of signal events (for a given confidence / credibility interval)

Some experiments quote also:

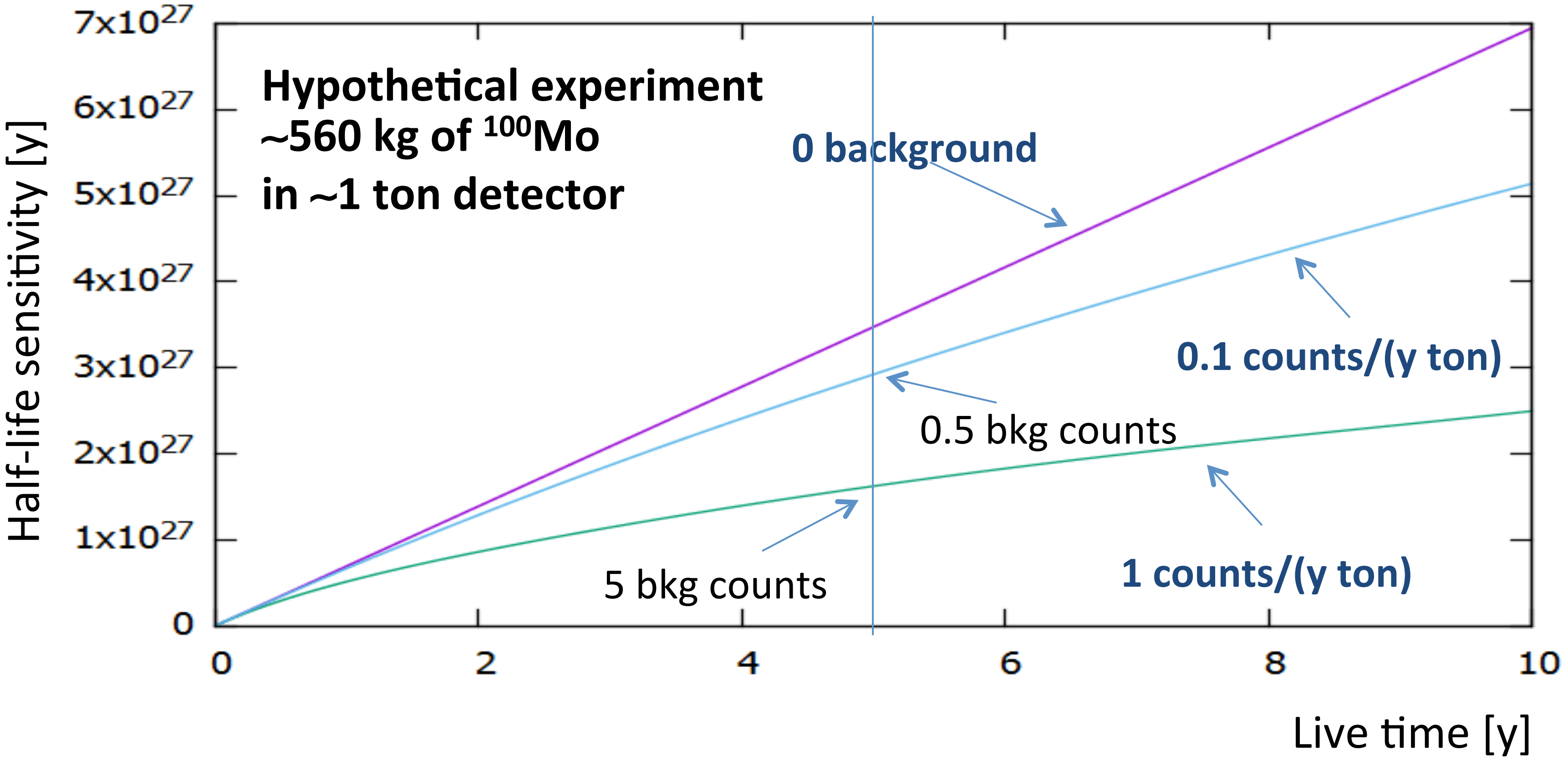
Discovery sensitivity: the value of $T_{1/2}$ or $m_{\beta\beta}$ for which the experiment has a 50% chance to measure a signal with a significance of at least 3 σ

(large uncertainty due to nuclear physics)

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

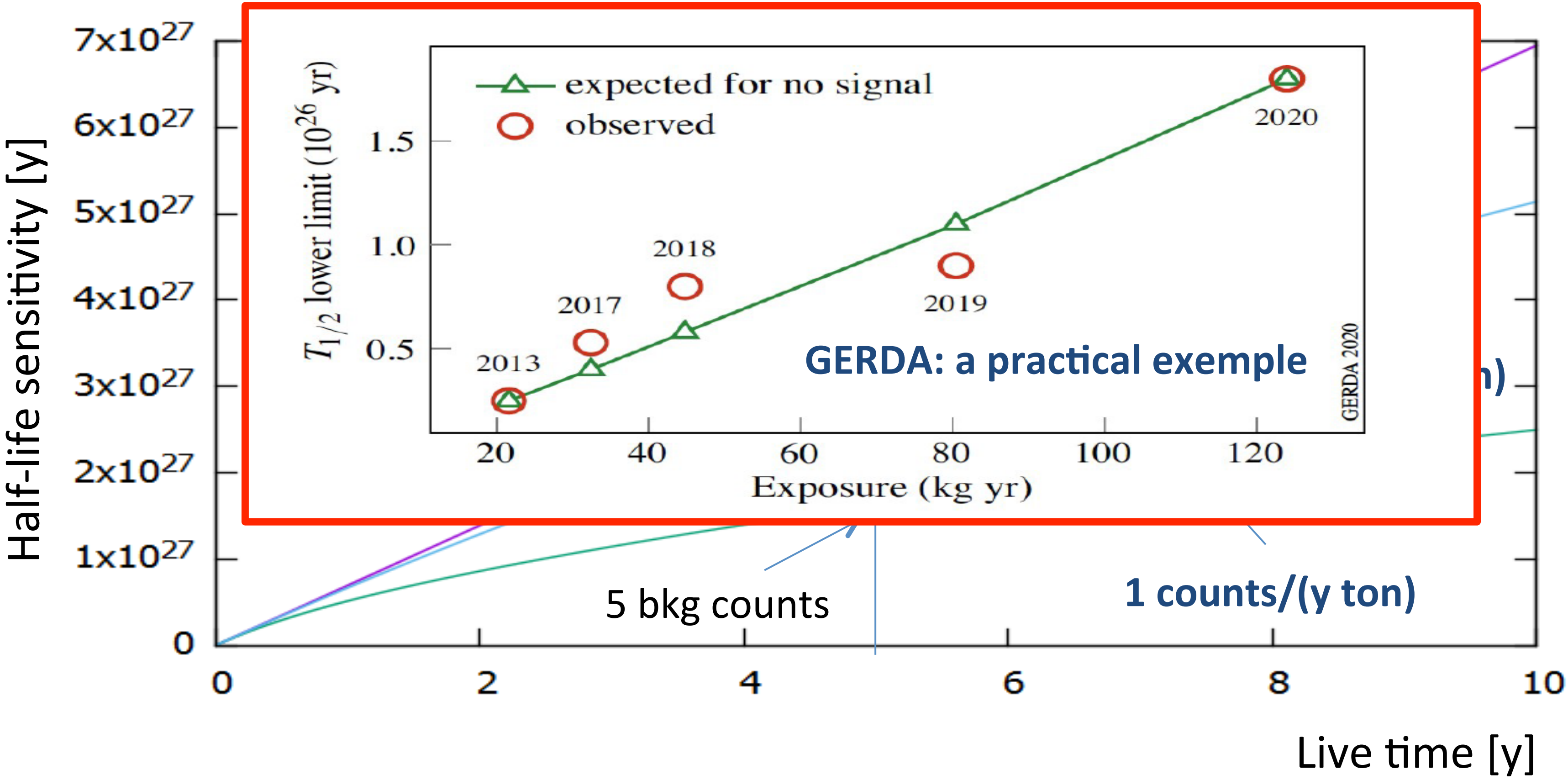
If you reach a limit **M***
in 5 y,
you have to measure
75 more years to get
M*/2

Effect of the background on the sensitivity



Hypothetical experiment
~560 kg of ^{100}Mo
in ~1 ton detector

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 $\longleftrightarrow T_{1/2}$ [^{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

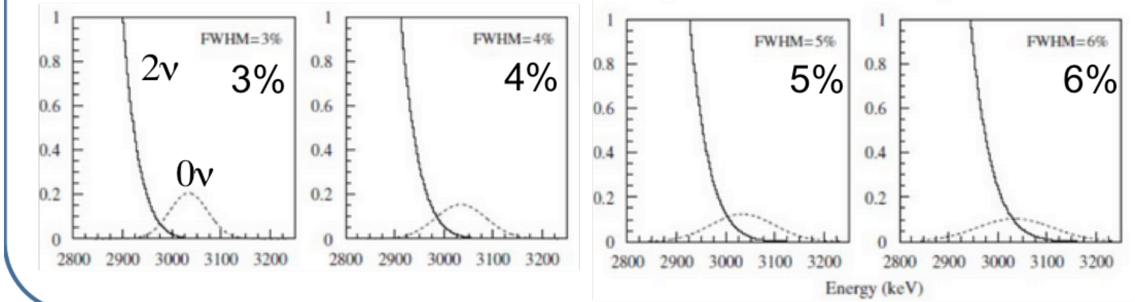
Quality and depth of the underground lab
Dedicated shielding are often required

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 x10^{18} y

Fastest 2ν process

Currently competing technologies

① **Source dilution in a liquid scintillator** →

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

② **TPCs** →

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

③ **Semiconductor detectors**

④ **Bolometers**

→

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

Currently competing technologies

① **Source dilution in a liquid scintillator** →

- Without inner balloon (SNO+)
- With inner balloon (KamLAND-Zen)
- With inner balloon + Cherenkov (Theia)
- Opaque scintillator (LiquidO)

② **TPCs** →

- High pressure gas →
  - Xe cylindrical (NEXT, PANDA-X-III, AXEL)
  - Xe spherical (R2D2)
  - SeF_6 (NνDEx)
- Liquid Xe (EXO-200, nEXO)
- Double phase Xe (DARWIN, LZ)

③ **Semiconductor detectors** →

- Ge diodes →
  - Immersed in LAr (GERDA, LEGEND-200/1000)
  - Conventional cryostat (MAJORANA)
- Se CCDs (SELENA)
- CdZnTe (COBRA)

④ **Bolometers** →

- Pure bolometers (CUORE)
- Scintillating bolometers (CUPID-0, CUPID-Mo, CUPID, AMoRE, CANDLES)
- Innovative bolometers (CROSS, BINGO)

Currently competing technologies

STOPPED / ONGOING

① **Source dilution in a liquid scintillator**
  - Without inner balloon (SNO+)
  - With inner balloon (**KamLAND-Zen**)
  - With inner balloon + Cherenkov (Theia)
  - Opaque scintillator (LiquidO)

② **TPCs**
  - High pressure gas
    - Xe cylindrical (NEXT, PANDA-X-III, AXEL)
    - Xe spherical (R2D2)
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Currently competing technologies

COMMISSIONING

① **Source dilution in a liquid scintillator**
- Without inner balloon (**SNO+**)
- With inner balloon (**KamLAND-Zen**)
- With inner balloon + Cherenkov (Theia)
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② **TPCs**
- High pressure gas
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④ **Bolometers**
- Pure bolometers (**CUORE**)
- Scintillating bolometers (**CUPID-0**, **CUPID-Mo**, CUPID, AMoRE, CANDLES)
- Innovative bolometers (CROSS, BINGO)

Currently competing technologies

CDR/TDR level

① **Source dilution in a liquid scintillator**
- Without inner balloon (**SNO+**)
- With inner balloon (**KamLAND-Zen**)
- With inner balloon + Cherenkov (Theia)
- Opaque scintillator (LiquidO)

② **TPCs**
- High pressure gas
    - Xe cylindrical (**NEXT**, PANDA-X-III, AXEL)
    - Xe spherical (R2D2)
    - SeF_6 (NνDEx)
- Liquid Xe (**EXO-200**, **nEXO**)
- Double phase Xe (DARWIN, LZ)

③ **Semiconductor detectors**
- Ge diodes
    - Immersed in LAr (**GERDA**, **LEGEND-200/1000**)
    - Conventional cryostat (**MAJORANA**)
- Se CCDs (SELENA)
- CdZnTe (COBRA)

④ **Bolometers**
- Pure bolometers (**CUORE**)
- Scintillating bolometers (**CUPID-0**, **CUPID-Mo**, **CUPID**, **AMoRE**, CANDLES)
- Innovative bolometers (CROSS, BINGO)

Currently competing technologies

R&D / INITIAL CONCEPTION

① **Source dilution in a liquid scintillator**
- Without inner balloon (**SNO+**)
- With inner balloon (**KamLAND-Zen**)
- With inner balloon + Cherenkov (**Theia**)
- Opaque scintillator (**LiquidO**)

② **TPCs**
- High pressure gas
  - Xe cylindrical (**NEXT**, **PANDA-X-III**, **AXEL**)
  - Xe spherical (**R2D2**)
  - SeF_6 (**NνDEx**)
- Liquid Xe (**EXO-200**, **nEXO**)
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- Pure bolometers (**CUORE**)
- Scintillating bolometers (**CUPID-0**, **CUPID-Mo**, **CUPID**, **AMoRE**, **CANDLES**)
- Innovative bolometers (**CROSS**, **BINGO**)

Current situation

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

KamLAND-Zen - $T_{1/2} > 2.3\times10^{26}$ y
https://arxiv.org/pdf/2203.02139.pdf)

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

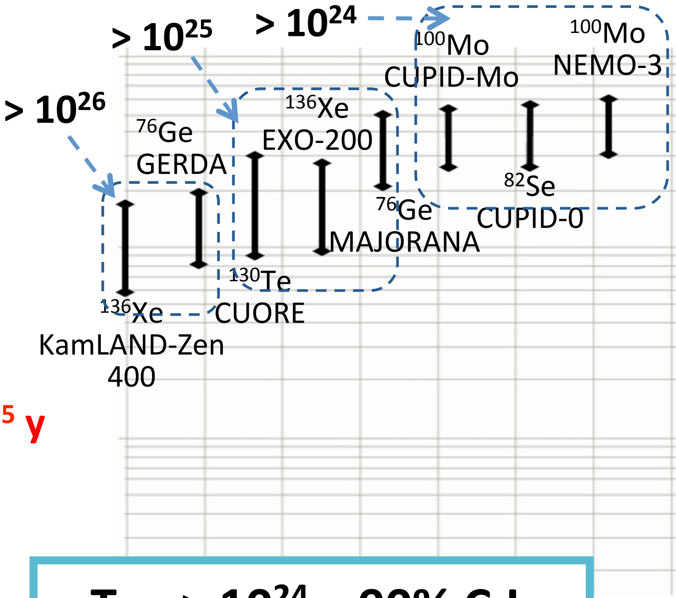
MAJORANA dem. - $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

CUORE - $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

CUPID-0 - $T_{1/2} > 4.7\times10^{24}$ y
L. Pagnanini, TAUP 2021

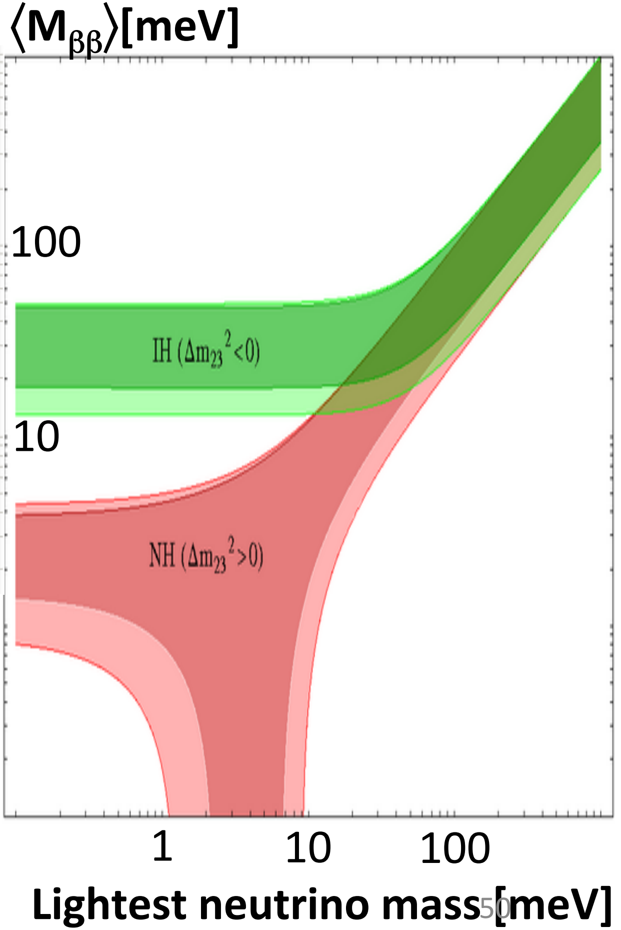
CUPID-Mo - $T_{1/2} > 1.8\times10^{24}$ y
B. Welliver, TAUP 2021

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 CUORE



Overview of the current/future experiments

Emphasis on **7 promising research lines**

① KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen **^{136}Xe**

② SNO+ → SNO+-phase II **^{130}Te**

Source dilution in a liquid scintillator

③ EXO-200 → nEXO

④ NEXT-White → NEXT-100 → NEXT-HD / NEXT-BOLD

^{136}Xe

Xe TPCs

⑤ GERDA / MAJORANA dem. → LEGEND-200 → LEGEND-1000 **^{76}Ge**

Semiconductor detectors – Ge diodes

⑥ CUPID-Mo **^{100}Mo** / CUPID-0 **^{82}Se** / CUORE **^{130}Te** → CUPID → CUPID Reach / CUPID 1t **^{100}Mo**

⑦ AMORE-I → AMORE-II **^{100}Mo**

Bolometers

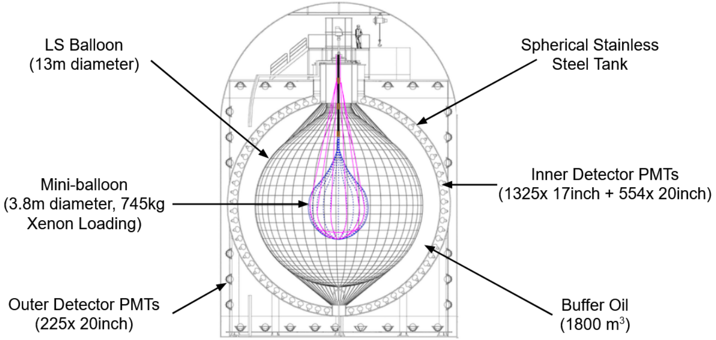
J. Phys.: Conf. Ser. 1468 012142 (2020)
H. Ozaki - Neutrino Telescope 2021
arXiv:2104.10452

KamLAND-Zen

Experimental concept

Enriched Xenon diluted (3 %) in liquid scintillator exploiting the existing KamLAND detector with the addition of a nylon balloon

- Energy resolution: **ΔE(σ) ~7%/√E(MeV) – 4.5%@$Q_{\beta\beta}$ ~ 10% FWHM**
- Single event position – **Vertex resolution 15 cm/ √E(MeV)**



KamLAND-Zen 400 – Kamioka, Japan (stopped)

350 kg of ^{136}Xe – Leading experiment

$T_{1/2}$ > 1.07×10^{26} y
$m_{\beta\beta}$ < 60 – 160 meV

Background:

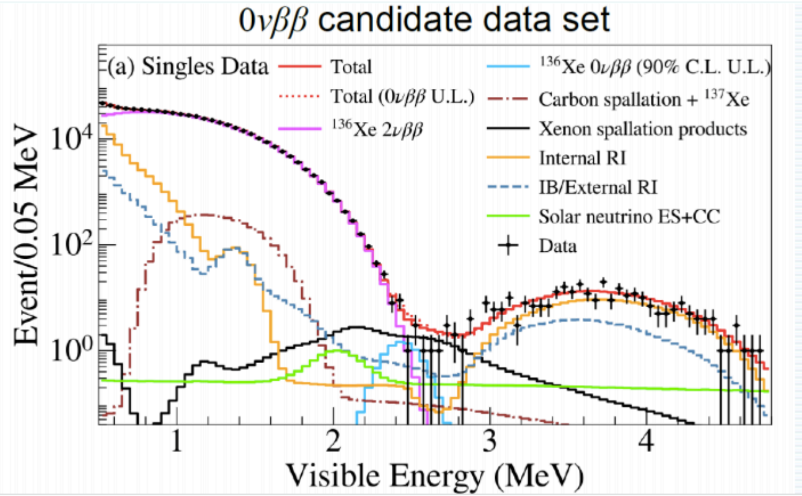
- 2νββ decay of ^{136}Xe
- Xe-LS, IB and outer-LS radioactive impuritities
- Cosmogenic: muon-spallation
- Solar neutrino electron scattering

KamLAND-800

$T_{1/2}$ > 2.3×10^{26} y
$m_{\beta\beta}$ < 36 – 156 meV

New points

- More isotope – **745 kg of ^{136}Xe**
- New balloon (2X larger, more radiopure)
- Improved analysis



KamLAND2-Zen

$T_{1/2}$ > 2×10^{27} y

- 1 ton of ^{136}Xe – 5X brighter → 2X better ΔE
- $m_{\beta\beta}$ < 20 meV

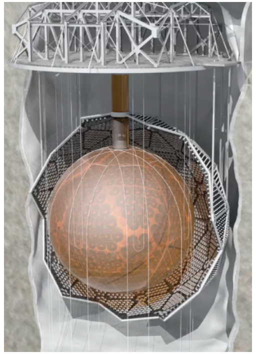
arXiv:2104.11687v2
TAUP 2021, M. Chen

SNO+

S.B. Biller – SNOLAB Future Project Workshop – May 2021

Experimental concept

Re-use the acrylic vessel, the PMT array and the electronics of the SNO detector at SNOLAB with a new target:



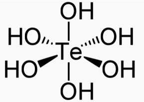
natural-Te-loaded liquid scintillator

- ➢ 780 tons of scintillator
- ➢ 3.9 tons of natural tellurium
- ➢ → **1.3 tons of ^{130}Te** (34% I.A.)

→ Scintillator purification system

→ Novel metal loading technique

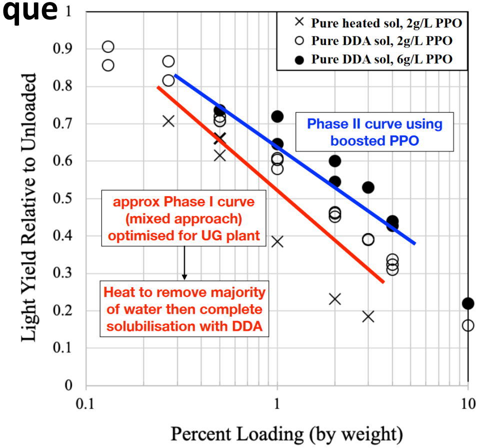
Telluric acid TeA



Purification

Reaction with 1.2-butanediol (BD)

Organo-metallic complex (TeBD) soluble in LAB
(0.5% mass loading)



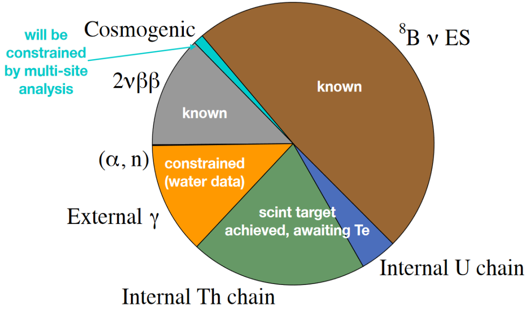
SNO+ consists of three phases

1. **Pure-water phase** (from May 2017)
2. **Liquid scintillator phase** without Te (ongoing)
3. **Te phase** (from 2022) – Study of $2\nu\beta\beta$ and $0\nu\beta\beta$

→ Precise background information

ΔE = 190 keV FWHM @$Q_{\beta\beta}$ ~ 7.5 % FWHM

Background budget and sensitivity



9.5 counts/y in ROI

5 y sensitivity
1.9×10^{26} y
$m_{\beta\beta} < 30 - 104$ meV

SNO+-phase II (start in 2026) – same set-up

- ➢ 0.5% → **3%**
  Te concentration (8 t of ^{130}Te)
- ➢ Improve transparency

5 y sensitivity
1×10^{27} y
$m_{\beta\beta} < 13 – 45$ meV

preCDR - arXiv:1805.11142v2
arXiv:2106.16243
Nature 569, 203–207 (2019)

nEXO

Experimental concept

Single phase enriched LXe TPC

- Energy resolution **ΔE(σ) ~ 0.8%@$Q_{\beta\beta}$ ~1.9% FWHM**
- Measurement of both charge and scintillation
- **Single site** (including signal) **vs. multi site events** (background)
- Multi-dimensional analysis using energy, 3D position and topology

nEXO is built on the successful **EXO-200** – **WIPP, US**

150 kg of ^{136}Xe – $T_{1/2} > 3.5\times10^{25}$ y – $m_{\beta\beta} < 93 - 286$ meV

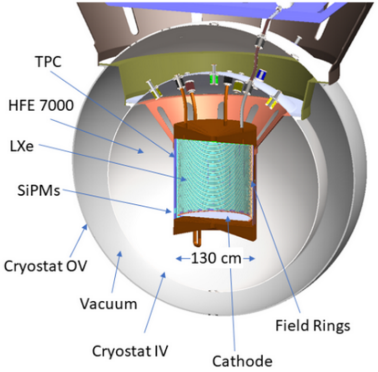
Proposed at **SNOLab**

Major upgrades with respect to EXO-200

- More isotope – **~5000 kg of ^{136}Xe**
- Improvement in light sensors (LAAPDs→SiPM)
- Increased light collection
- Improvement in radiopurity (electroformed Cu)
- Cold electronics

	EXO-200	nEXO
Fiducial Mass [kg]	74.7	3281
Energy resolution σ/$Q_{\beta\beta}$ [%]	1.2%	0.8%

LXe self shielding



Background dominated by Rn outgassing and intrinsic radioactivity

10 y sensitivity

1.35×10^{28} y

$m_{\beta\beta} < 5 - 15$ meV

Tagging of individual **^{136}Ba daughter**

Demonstrated by fluorescence in solid Xenon
Not in the nEXO baseline

preCDR - arXiv:1805.11142v2
arXiv:2106.16243
Nature 569, 203–207 (2019)

nEXO

Experimental concept

Single phase enriched LXe TPC

- Energy resolution **ΔE(σ) ~ 0.8%@$Q_{\beta\beta}$ ~1.9% FWHM**
- Measurement of both charge and scintillation
- **Single site** (including signal) **vs. multi site events** (background)
- Multi-dimensional analysis using energy, 3D position and topology

nEXO is bui

150 kg of ^{13}

Proposed a

Major upgr

- More iso
- Improve
- Increase
- Improvement in radiopurity (electroformed Cu)
- Cold electronics

Double-phase Xe TPCs mainly conceived for direct Dark Matter detection can provide competitive results on $0\nu\beta\beta$ ^{136}Xe (with **natural Xenon**)
Sensitivities that are about 1-2 orders of magnitude lower than nEXO’s

DARWIN	*Eur. Phys. J. C 80, 808 (2020)*
LZ	*Phys. Rev. C 102, 014602 (2020)*
PANDAX-4T	*Ke Han, TAUP 2021*

	EXO-200	nEXO
Fiducial Mass [kg]	74.7	3281
Energy resolution σ/$Q_{\beta\beta}$ [%]	1.2%	0.8%

LXe self shielding

Background dominated by Rn
g and
oactivity

itivity
^{28} y
5 meV

Demonstrated by fluorescence in solid Xenon
Not in the nEXO baseline

J. High Energ. Phys. 2019, 230 (2019)
J. High Energ. Phys. 2019, 52 (2019)

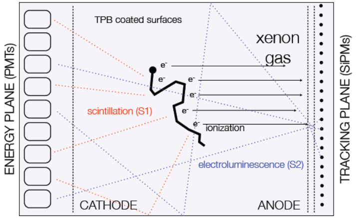
NEXT

arXiv:1906.01743
Phys. Rev. Lett. 120, 132504 (2018)

Experimental concept

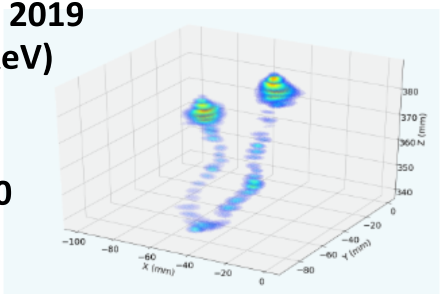
High pressure (10-15 bar) enriched Xe TPC

- Primary scintillation ($t_0 \rightarrow$ z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane) → only light detection, also for the charge readout

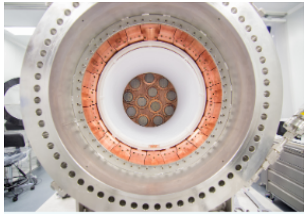


Proof of concept: NEXT-White (from 2016) – LSC, Spain

- 5 kg prototype – **enriched Xe from 2019**
- **ΔE < 1% FWHM in the ROI (< 25 keV)**
- **Event topological reconstruction**
- $2\nu\beta\beta$ detected at more than 5σ
- **Infrastructure usable for NEXT-100**



Real ββ event



NEXT-100 (funded) – LSC, Spain (2022-2025)

Upscaling of NEXT-White

- More isotope – **~97 kg of enr Xe gas (^{136}Xe: 90%)**
- 15 bar operation
- Same structure/technology of NEXT-White
- Larger vessel, 60x PMTs and 5600x SiPMs

400 kg×y sensitivity

1×10^{26} y **$m_{\beta\beta} < 60 - 160$ meV**

NEXT-HD (High Definition) – start in 2026

- Up to 1 ton enriched Xe gas at 20 bar
- Xe-He mixture: lower diffusion, better definition

Target sensitivity: 2×10^{27} y **6 ton×y**

NEXT-BOLD (Barium On Light Detection)

- Ba tagging by **SMFI** (Single Molecule Fluorescence Imaging) was proved
- Background free

Target sensitivity: 8×10^{27} y **10 ton×y**

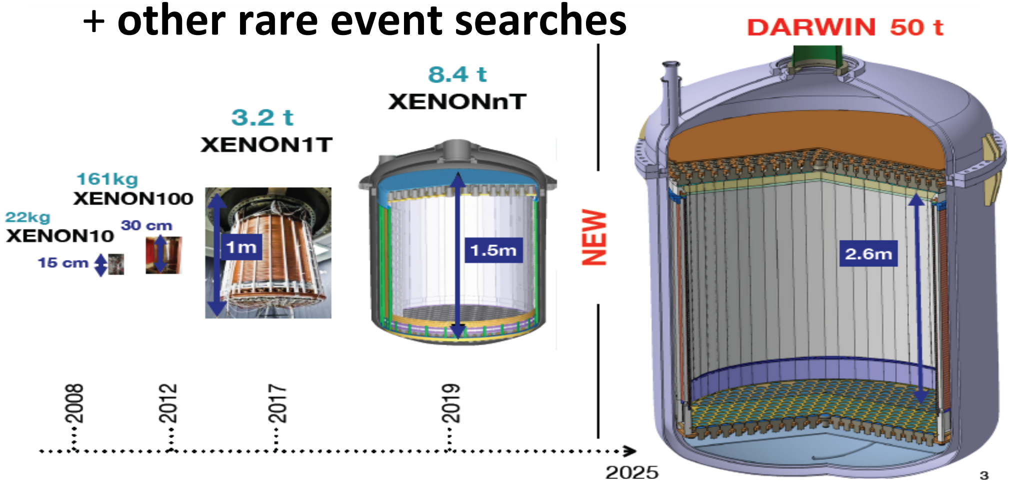
^{136}Xe

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

DARWIN as a neutrinoless double beta decay experiment

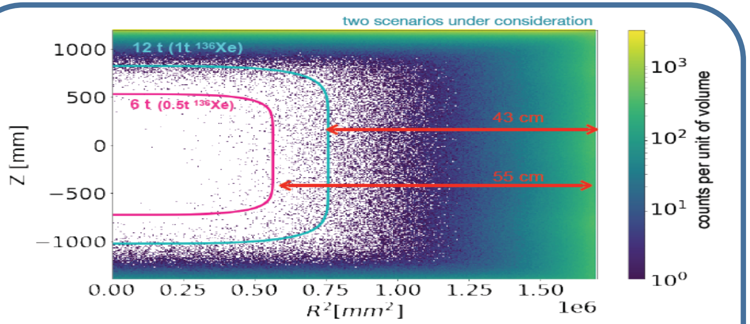
Dark matter + double beta decay + other rare event searches

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

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

GERDA → LEGEND

arXiv:2107.11462v1

AIP Conference Proceedings 1894, 020027 (2017)

Experimental concept

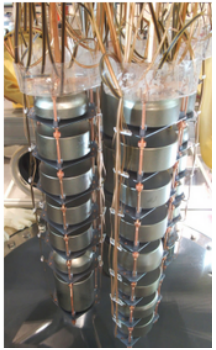
High purity naked Ge detectors immersed in instrumented LAr

- Energy resolution ΔE ~ 3 keV FWHM @$Q_{\beta\beta}$
- Pulse shape discrimination: **multi site vs. single site events**
- Anticoincidence with **LAr active shield**, instrumented with
  - Wavelength shifting fiber shroud coupled to SiPMs
  - PMTs on top and bottom of the setup

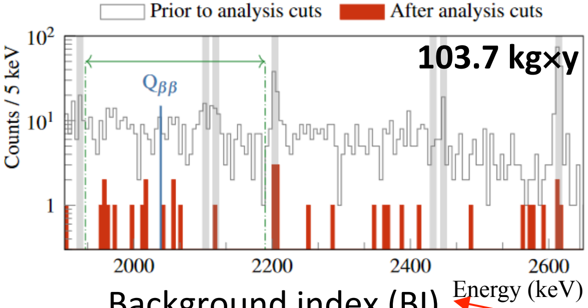
GERDA - **LNGS, Italy**

35 kg of ^{76}Ge – Leading experiment in terms of half-life

$T_{1/2} > 1.8\times10^{26}$ y - $m_{\beta\beta} < 79 – 180$ meV



37 HP Ge detectors



Background index (BI)

$5.2^{+1.6}_{-1.3} \times 10^{-4}$ c/(keV kg y)

Lowest in all ββ experiments

LEGEND-200 – data taking: end 2021 – start 2022

- Adopt GERDA detector configuration
- **Re-use GERDA infrastructure at LNGS**
- Follow MAJORANA selection of radiopure parts
- MAJORANA electronics and low threshold
- ~ **200 kg** of ^{76}Ge (partial re-use)
- **New detector type**, already tested in GERDA
  ICPC detector, **> 2 kg** vs. previous 0.7-0.9 kg
  → same energy resolution and PSD capability

LEGEND-1000 – SNOLAB or LNGS

- Same technology, **new larger infrastructure**
- Phased approach, up to **1000 kg of ^{76}Ge**

LEGEND-200	LEGEND-1000
BI: 2× 10^{-4} c/(keV kg y)	BI: 10^{-5} c/(keV kg y)
$T_{1/2} > 10^{27}$ y in 5 y	**$T_{1/2} > 1.3\times10^{28}$ y** in 10 y
$m_{\beta\beta} < 34 – 78$ meV	**$m_{\beta\beta} < 9 – 21$ meV**

CUORE and CUPID demonstrators

B. Welliver, TAUP 2021
L. Pagnanini, TAUP 2021
Phys. Rev. Lett. 126, 181802 (2021)

Experimental concept - CUORE

Array of natural TeO_2 bolometers at 10 mK

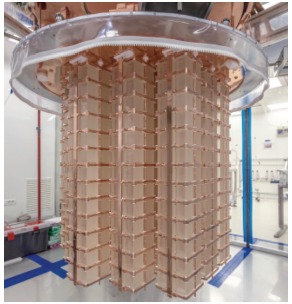
- Built on the precursor CUORICINO experiment
- **988 TeO_2 crystals** in **19 towers – 206 kg of ^{130}Te**
- $\Delta E \sim 7.8$ keV FWHM $@Q_{\beta\beta}$ – $Q_{\beta\beta}$=2527 keV
- Background index **1.49×10^{-2} c/(keV·kg·y)**

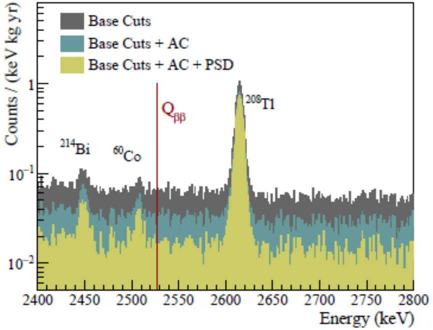
↑ Dominated by **energy-degraded surface α's**

CUORE - LNGS, Italy *arXiv:2104.06906*

Exposure: **1038.4 kg × y –** Record for bolometers

$T_{1/2} > 2.2\times10^{25}$ y – $m_{\beta\beta} < 90 – 305$ meV

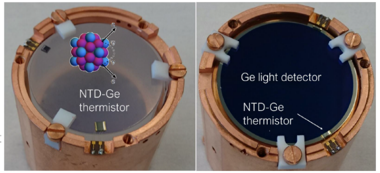




Target sensitivity: **9×10^{25} y – $m_{\beta\beta} < 50 – 130$ meV**

Experimental concept – CUPID-Mo (LUMINEU R&D)

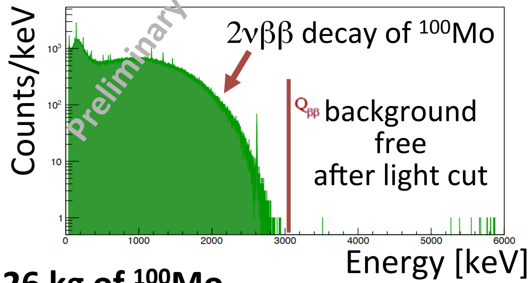
2 changes wrt CUORE:



① **Pure bolometers → Scintillating bolometers**
(**reject α background**)

② **^{130}Te (TeO_2) → ^{100}Mo (enriched Li_2MoO_4)**

$Q_{\beta\beta}$=3034 keV > 2.6 MeV (**reject external γ background**)



CUPID-Mo - LSM, France

Exposure: **2.71 kg × y**

NEW **$T_{1/2} > 1.8\times10^{24}$ y**
$m_{\beta\beta} < 280 – 490$ meV

- **20 Li_2MoO_4 crystals – 2.26 kg of ^{100}Mo**
- Energy resolution **$\Delta E \sim 7.8$ keV FWHM $@Q_{\beta\beta}$**

CUPID-0 - LNGS, Italy Zn^{82}Se **NEW** **$T_{1/2} > 4.7\times10^{24}$ y**

First scintillating bolometer demonstrator **$m_{\beta\beta} < 276 – 570$ meV**

arXiv:1907.09376

CUPID

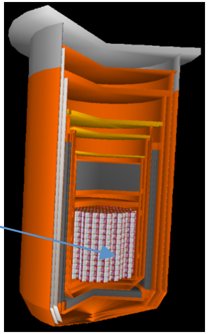
Experimental concept

Built on the success of CUPID-Mo + CUORE

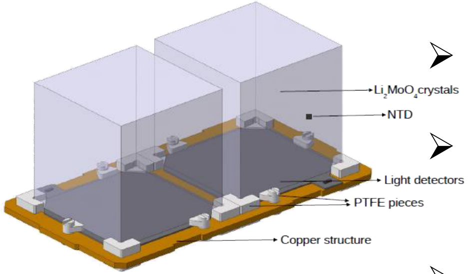
Li_2MoO_4 scintillating bolometer technology, demonstration of
- energy resolution
- crystal radiopurity
- α rejection
- reproducibilty

Ton-scale bolometric experiment is possible

Reuse CUORE infrastructure + electronics and data analysis tools



CUPID – LNGS, Italy



ΔE ~ 5 keV FWHM @$Q_{\beta\beta}$

- 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
- **Bolometric Ge light detectors** as in CUPID-Mo, CUPID-0

Data driven background model

- Information from CUPID-Mo, CUPID-0
- CUORE background model (same infrastructure!)

Projected background index: **1×10^{-4} c/(keV kg y)**

Critical background component: **random coincidence of $2\nu\beta\beta$ events** (^{100}Mo fastest $2\nu\beta\beta$ emitter: $T_{1/2} = 7.1\times10^{18}$ y)

10 y discovery sensitivity

1.1×10^{27} y **$m_{\beta\beta} < 12 – 20$ meV**

Possible follow-up of CUPID

CUPID-reach - Same sensitive mass and cryostat as CUPID

Background improvement by factor 5

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

CUPID-1T - 1 ton isotope → new cryostat

Background improvement by factor 20

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

Criticalities:
- $2\nu\beta\beta$
- Surface events

AMoRE and other bolometric efforts

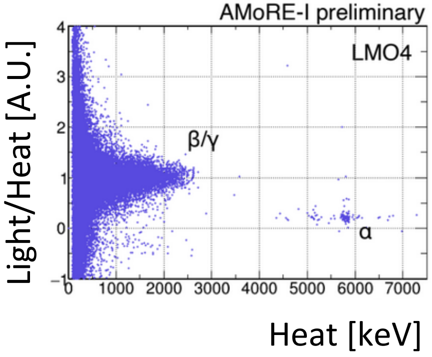
J. Phys.: Conf. Ser. 1468, 012130 (2020)
JINST 15 C08010 (2020)

Experimental concept

- ^{100}**Mo**-containing scintillating bolometers
- Initially chosen compound: $\mathbf{^{48depl}Ca^{100}MoO_4}$
- $\mathbf{Li_2{}^{100}MoO_4}$ is the only compound foreseen in **AMORE-II**
- Heat readout based on fast **MMC**
  - → $2\nu\beta\beta$ random coincidences: negligible background
- Energy resolution **ΔE ~ 10-15 keV FWHM @$\mathbf{Q_{\beta\beta}}$**

AMORE-I – Y2L lab – started in Aug 2020 - stop in 2022

13x $^{48depl}Ca^{100}MoO_4$ (CMO, 4.6 kg)
5x $Li_2{}^{100}MoO_4$ (LMO, 1.6 kg)
→ **3 kg of ^{100}Mo**



AMORE-II – 2022 - 2027

Secured **110 kg of ^{100}Mo** – 596x $Li_2{}^{100}MoO_4$ crystals
New cryostat and UG lab (Yemilab)

Sensitivity: 8×10^{26} y
$m_{\beta\beta}$ < 13 – 25 meV

Techniques for background rejection in future TeO_2 / Li_2MoO_4 based experiments

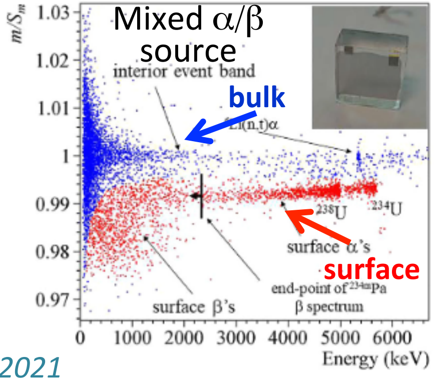
CROSS Canfranc

Reject **surface events** by **PSD assisted by metal film coating**

Proof of concept achieved

^{100}Mo 6 kg demonstrator in preparation

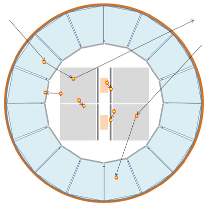
Appl. Phys. Lett. 118, 184105 (2021

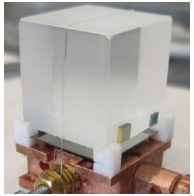


BINGO Modane

Luminescent bolometers

- **Internal active shield**
  - → mitigate γ background inTeO_2
- **Revolutionary assembly** to reject surface background
- **Enhanced-sensitivity** light detectors





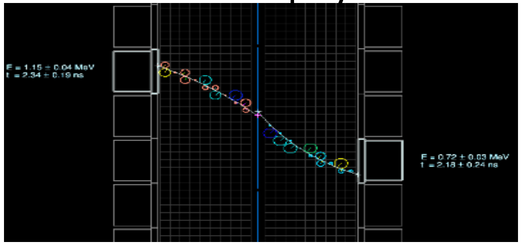
^{82}Se, ^{150}Nd
source ≠ detector

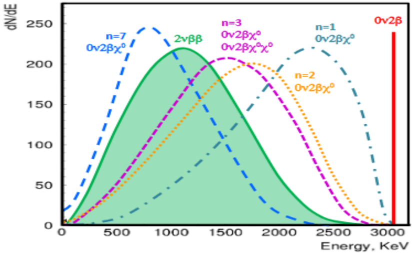
SuperNEMO

NIM A958, 162115 (2020)

- 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)

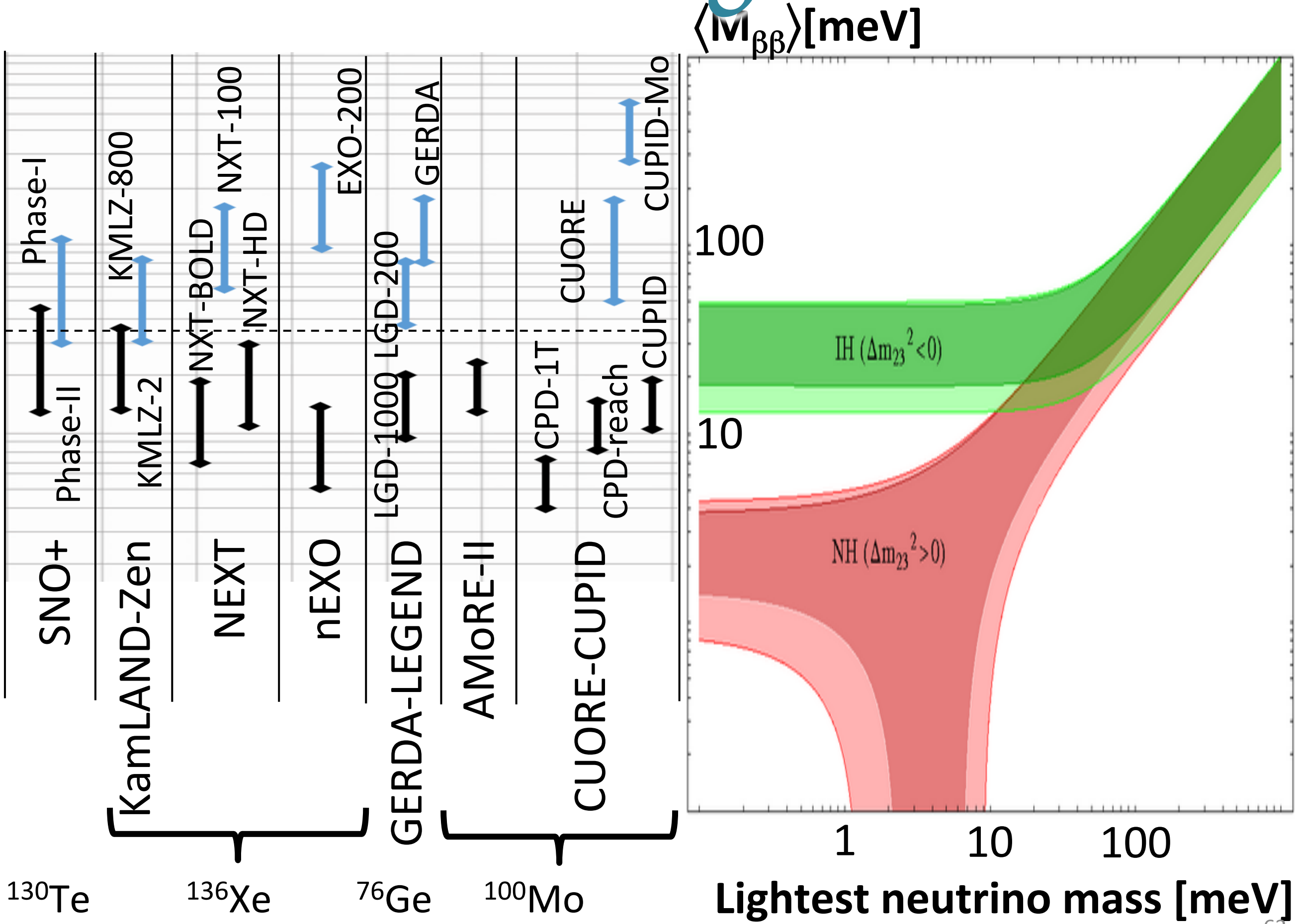
Prospects

- 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

From the current to the next generation

Current generation
(concluded – running – on-commissioning projects)

Next generation
(projects to be started in the next decade)



Conclusions and prospectives

- $0\nu\beta\beta$ is a crucial process for particle physics and cosmology
- Several approaches and technologies make this field very active
- Many projects will extend their sensitivity in the next years
- Next-generation experiments have a good discovery potential
- Stay tuned…

Neutrino flavor oscillations

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

Flavor eigenstates ≠ Mass eigenstates

Weak interaction

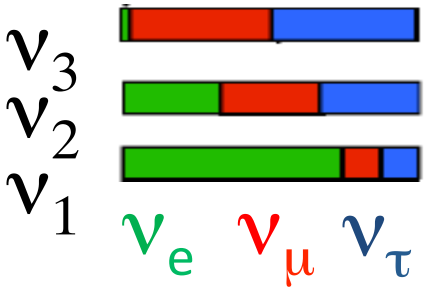
Propagation

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

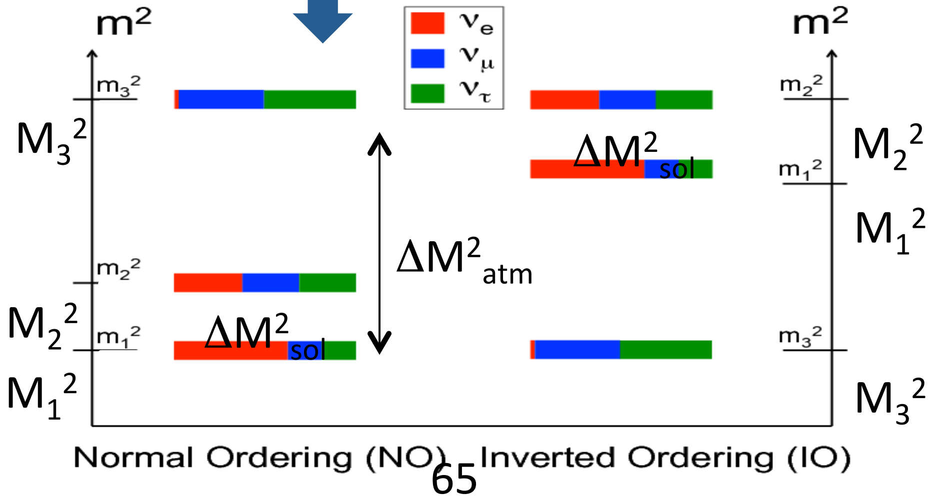
Neutrino flavor oscillations

Neutrino mixing matrix (PMNS)

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



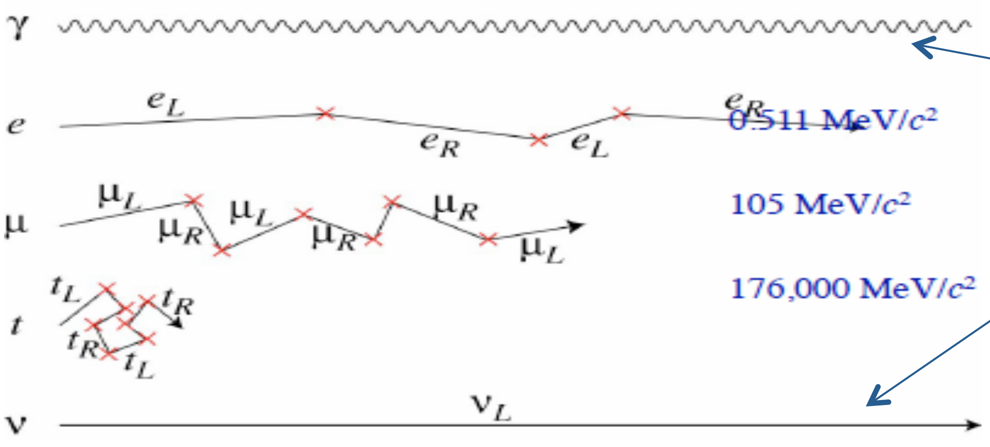
Neutrino mass ordering



In the Standard Model, neutrinos are massless

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

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

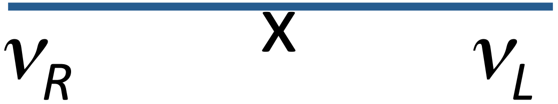
Giving masses to neutrinos

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

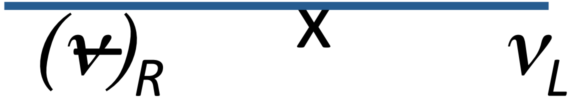


However, we are authorised to add a new mass term **only for neutrinos**

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:

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

Provides the Dirac and Majorana mass terms defined before

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

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

m_D must be of the same order of the charged lepton masses (Higgs mechanism)

M_R can be everywhere (GUT scale)

→ the condition **$M_R >> m_D$** 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**

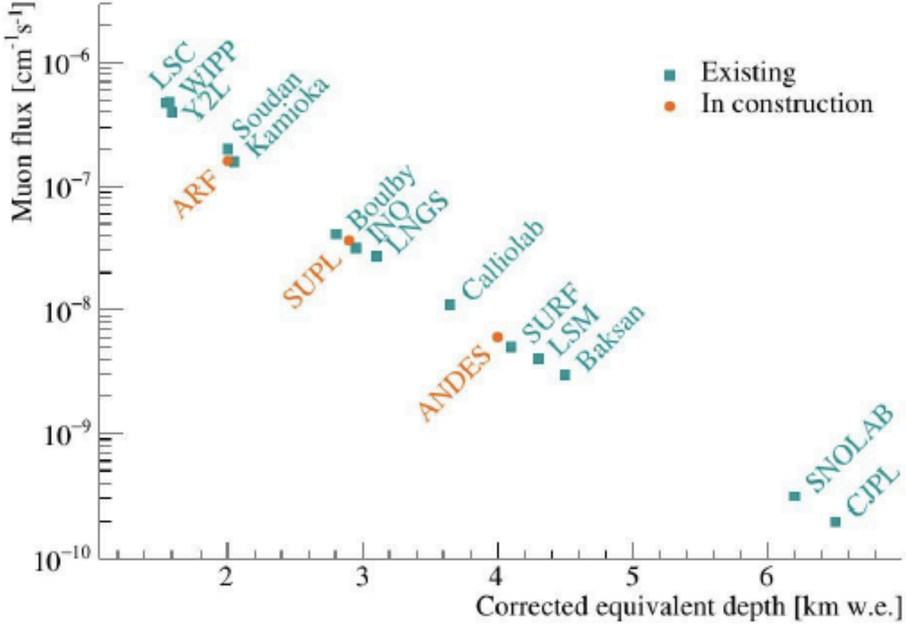
$$\nu_1 \sim \nu_L + \nu_L^c - (m_D / M_R)(\nu_R + \nu_R^c)$$

Eigenvectors

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

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

Cosmic ray background

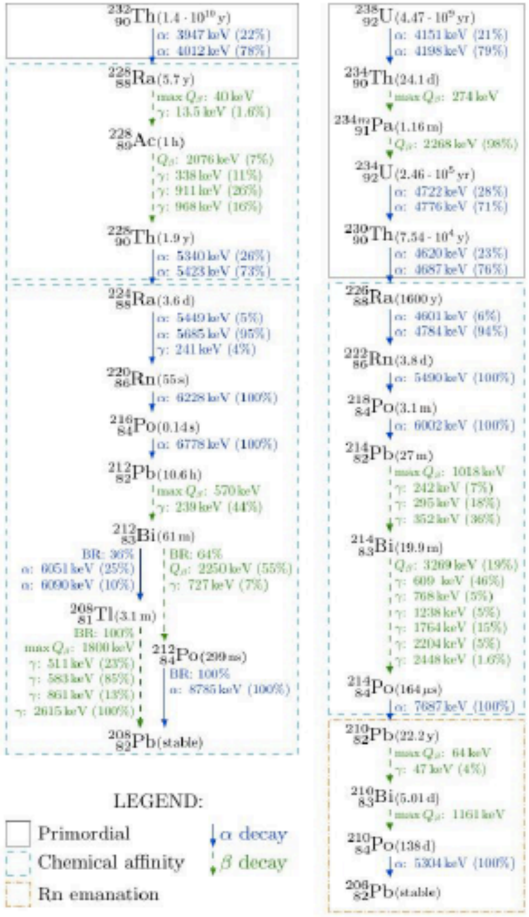


Residual backgrounds from cosmic in underground experiments:

- High energy muons (up to TeV)
  → Reconstruct muon tracks (monolithic)
  → Muon veto around granular detector
- Spallation products
  - Activate isotopes in the detector material prior to the installation underground
  - Activation in situ
    → Relevant for large volume scintillators
    → If the activated isotope decays quickly, search for delayed coincidences
  - High energy spallation neutrons
    → Well, this is a problem!

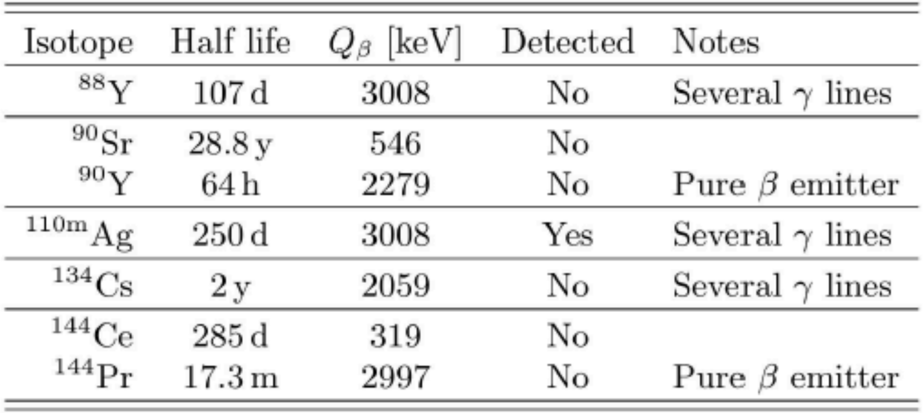
Background from actinides contamination

- Uranium and thorium contamination present in **many** materials
- Several particle types involved:
  - α between 4 and 9 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV, but summation possible
  - neutrons from (α,n) reactions
- Decay chains not always in equilibrium
  - Material exposure to air
    → ^{222}Rn deposition followed by ^{210}Pb accumulation
  - Surface cleaning
    → Pb removed, ^{210}Po remains
  - Mechanical or chemical processes in material bulk or surface
    → Accumulation of “chemically active” radium
- Possible suppression techniques:
  - Use cleaner materials and surfaces
  - Minimize exposure to radon
  - Particle identification to reject α
  - Event topology
  - Delayed coincidences



Man-made isotopes

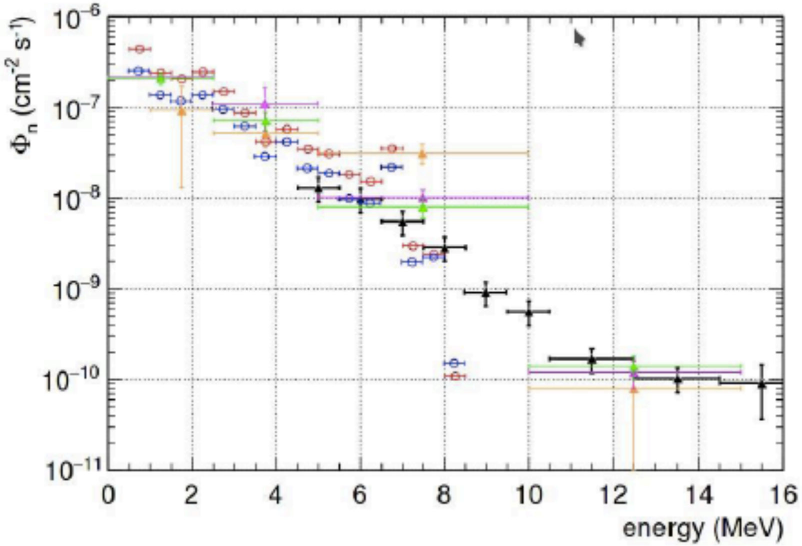
- Several man-made isotopes visible in ultra-low background experiments
- Background only from:
  - Isotopes decaying β with $Q_{\beta}>Q_{\beta\beta}$
  - Isotopes or decay chains with dominant half-life comparable to experiment lifetime
- So far, only ^{110m}Ag has been found



Isotope	Half life	Q_β [keV]	Detected	Notes
^{88}Y	107 d	3008	No	Several γ lines
^{90}Sr	28.8 y	546	No	
^{90}Y	64 h	2279	No	Pure β emitter
^{110m}Ag	250 d	3008	Yes	Several γ lines
^{134}Cs	2 y	2059	No	Several γ lines
^{144}Ce	285 d	319	No	
^{144}Pr	17.3 m	2997	No	Pure β emitter

Neutrons

Source	Location	Energy
^{238}U fission	Concrete or internal	<10 MeV
(α,n) reactions	Concrete or internal	<10 MeV
Spallation	Rock, concrete, …	up to GeV



Neutron suppression

- Passive shielding (polyethylene, boron, water) → good for neutrons <10 MeV
- Active shielding in liquid scintillator outer layer
- Add element with high neutron cross section (e.g. ^{6}Li) in active volume

Neutron backgrounds

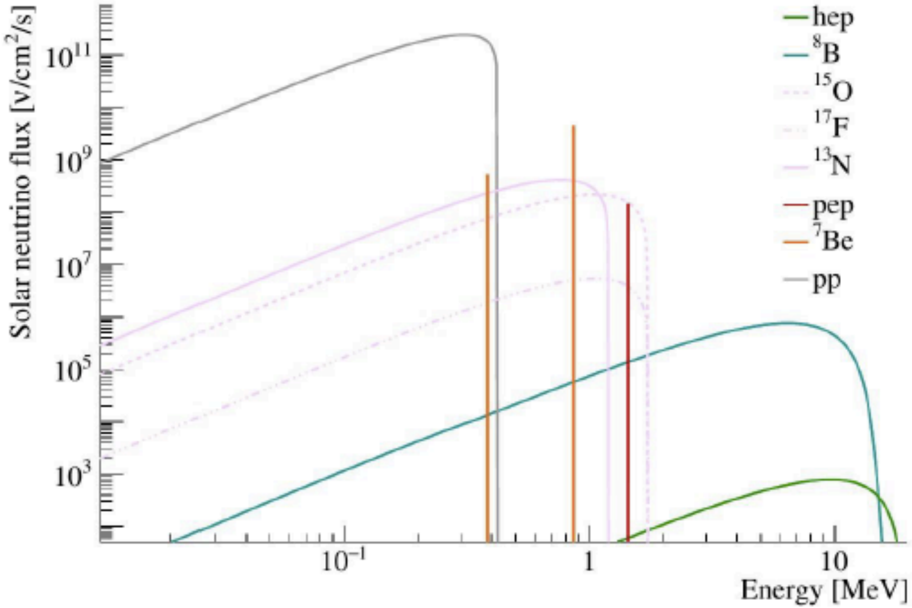
- In-situ isotope activation
- γ's from inelastic scattering or captures

Solar neutrinos

Elastic scattering

$$\nu + e^- \to \nu + e^-$$

- Only relevant for large scintillators
- Can be suppressed through signal directionality

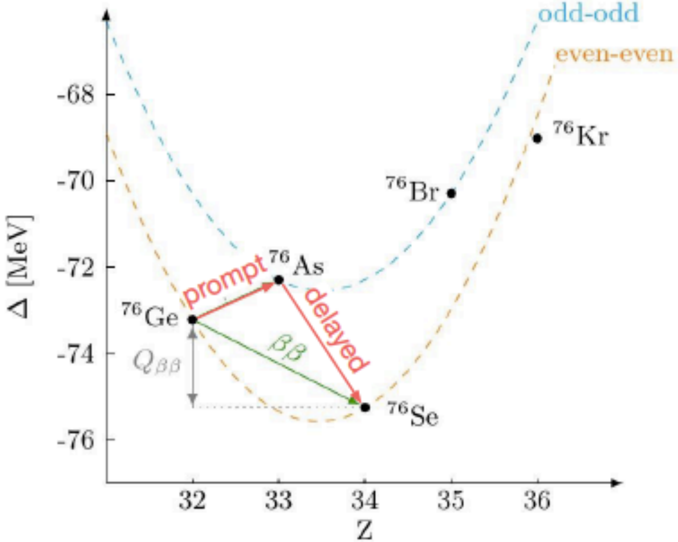


Charge Current

Prompt: $^{Z}A + \nu \to {}^{Z+1}A + e^- \, [+ \gamma(s)] + Q_\nu$

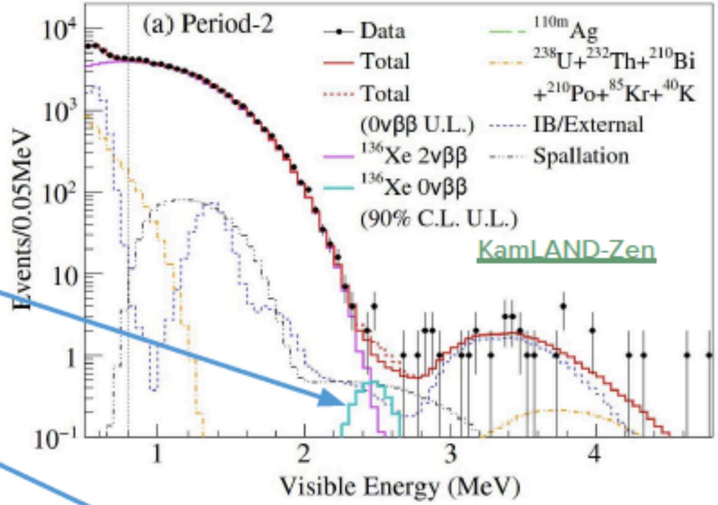
Delayed: $^{Z+1}A \to {}^{Z+2}A + \beta^- \, [+ \gamma(s)] + Q_\beta$

- Can be suppressed via topology and delayed coincidences, depending on isotope
- Not quite relevant, yet

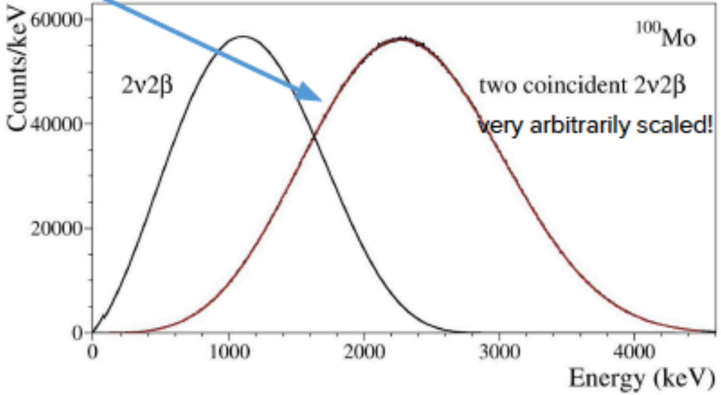


2νββ decay

- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⇒ Energy resolution
  - Pile-up of 2νββ events
    ⇒ Time resolution



KamLAND-Zen



D. M. Cherniak et al., EPJ C72 (2012) 1989

The goal of BINGO

- **BINGO will set the grounds for a large scale bolometric experiment searching for neutrinoless double-beta decay (0ν2β) using revolutionary technologies**
- **It aims to reduce dramatically the background in the region of interest, through:**

A revolutionary detector assembly:

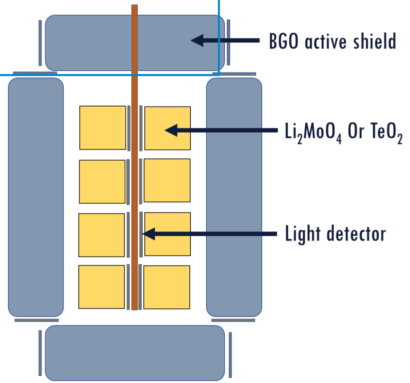
- Reduce the Cu material seen by the main absorber → reduction of the total surface radioactivity contribution
- Having a compact assembly → anticoincidence cuts

Neganov-Luke light detectors:

- Amplification of the tiny Cherenkov signal (TeO_2) → suppress alphas
- Higher sensitivity, lower energy threshold → suppress external γ background using the active shield

An active shield based on BGO or $ZnWO_4$ scintillators:

- Suppress the external gamma background (specifically essential for TeO_2)

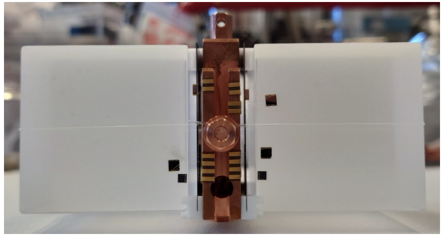


Bi-Isotopic approach: observation in 2 candidates → discovery + confirmation

Prototype tests

Nylon wire assembly

- Two 45mm cubic Li_2MoO_4 crystals fixed against PTFE pieces using nylon wire
- The PTFE pieces sandwich also Ge light detectors
- The test successfully validated the nylon wire assembly in terms of bolometric performance



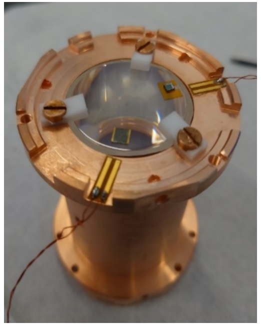
Performances	S (nV/keV)	FWHM bsln (keV)	FWHM @ 609 keV
LMO	58	4.9	7.2

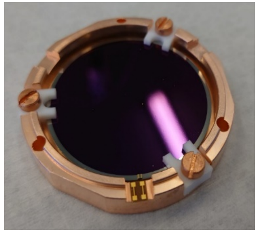
The bolometric performance was promising. 2 detectors modules (4 Li_2MoO_4) will be tested underground before moving to **MINI-BINGO**:

- new low-background cryogenic infrastructure at LSM
- 6 modules of Li_2MoO_4 and 6 modules of TeO_2 to be tested at **LSM** starting in 2023
- The physics volume is surrounded by 16 scintillating crystals on the lateral, 4 on the top and 4 on the bottom acting as an active shield
- 1-year run starting in 2024 to reach $b=10^{-4}$ c/keV/kg/y

Scintillating BGO or $ZnWO_4$ crystal prototype (IJCLab)

The test was performed to check the light yield and have a rough estimation of the energy threshold





- ∅30×60 mm crystals
- SiO coated LD for light collection

Crystal	LY (keV/MeV)	Threshold
BGO	28	10
$ZnWO_4$	14	25