The search for neutrinoless double-beta decay

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Part 1

Plan

- Neutrino physics and double beta decay
- Double-beta decay: Myths and Reality
- How to optimize an experiment
- What experiments are there?
- Some ideas about the not-so-immediate future

- *This is not a review talk; some examples are taken from various experiments with the main purposed of illustration.*
- *I do expect questions for the audience, you should expect grades, and rich prizes.*

Last 25 yrs: the age of ν physics

Discovery of ν flavor change

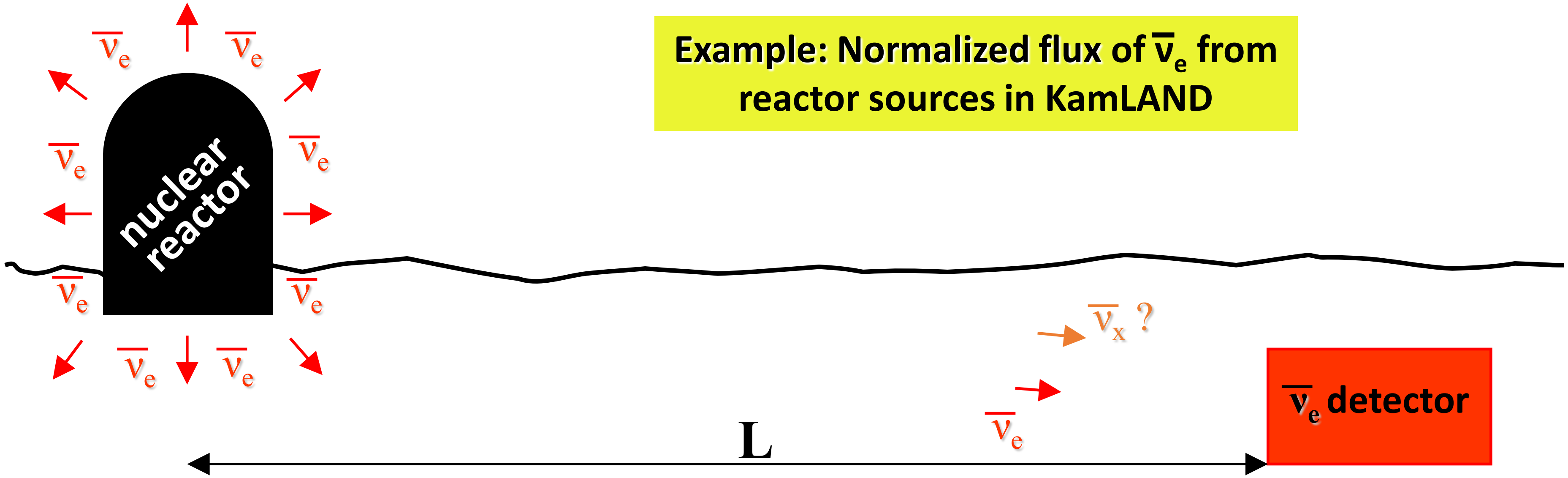
- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *Accelerator neutrinos (vacuum oscillation)*

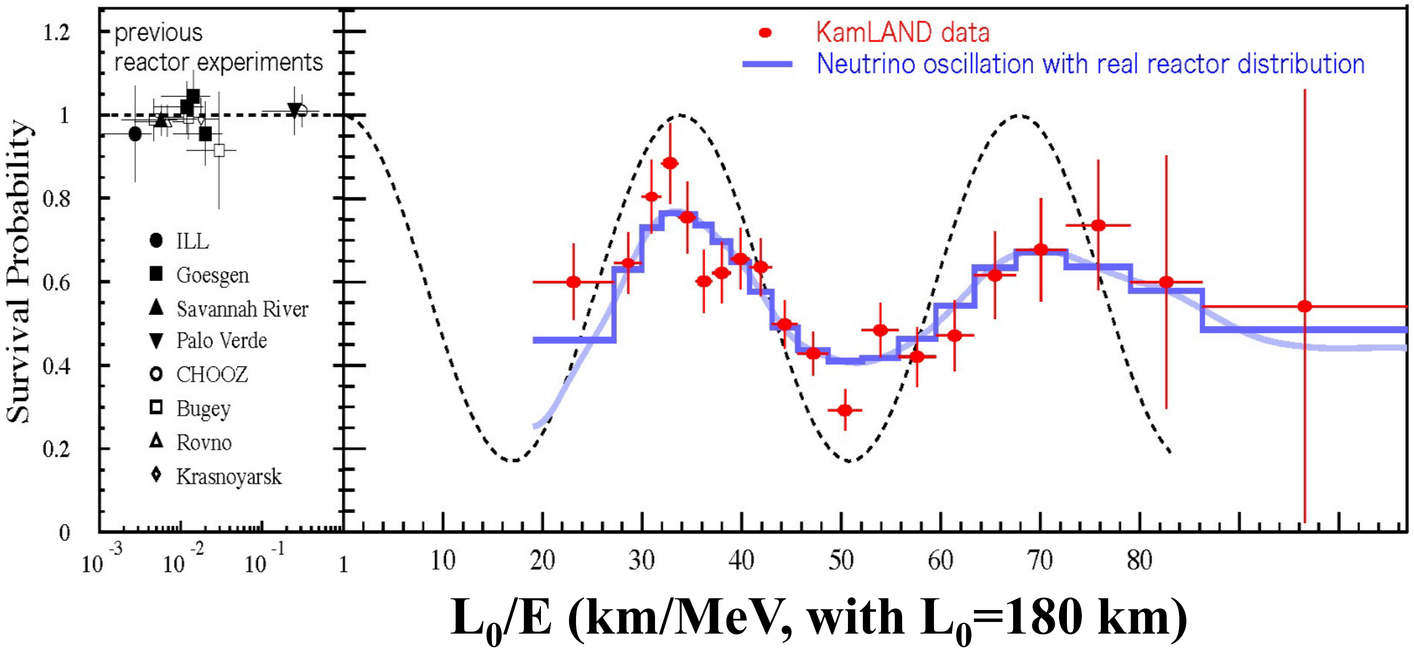
We also found that:

- **ν masses are non-zero**
- **there are 2.981±0.008 ν (Z lineshape)**
- **3 ν flavors were active in Big Bang Nucleosynthesis**
- **The Sun emits neutrinos as expected**

- **Supernovae emit neutrinos**

Example: Normalized flux of $\overline{\nu}_e$ from reactor sources in KamLAND





If $m_\nu \neq 0$ neutrinos show a different image depending on our vantage point:

- "Weak interaction eigenstate"

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

this is the state of definite flavor: interactions couple to this state

- "Mass eigenstate"

$$\begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

this is the state of definite energy: propagation happens in this state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

A source produces –say- ν_e
always via weak interactions

$$\nu_e$$

To see what propagates to the detector I have to project this flavor state onto the mass state using the matrix inverse of U

$$\nu_m = U^{-1} \nu_e$$

Now each of the ν_m will evolve in time as prescribed by the wave functions

$$\nu_{m1}(t) = e^{-i(E_1 t - p_1 L)}\nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(E_2 t - p_2 L)}\nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(E_3 t - p_3 L)}\nu_{m3}$$

note that the periodic term contains the neutrino mass via $E_i=m_ic^2$

So at the end of their flight -at the detector- the mix of ν_{m1}, ν_{m2}, ν_{m3} will not necessarily be the one that makes "exactly" ν_e !

The neutrinos are then detected via weak interactions so that we need to find again the composition in terms of ν_e, ν_μ, ν_τ

Formally

$$\left|\nu_j\right\rangle = \sum_{j'}\sum_{l} U_{lj} e^{-i(E_j t - p_j L)} U^*_{j'l}\left|\nu_{j'}\right\rangle$$

So, after some propagation one can "find" a neutrino of a flavor that was not originally there.

This is a pure quantum-mechanical effect, there is no classical interpretation of it.

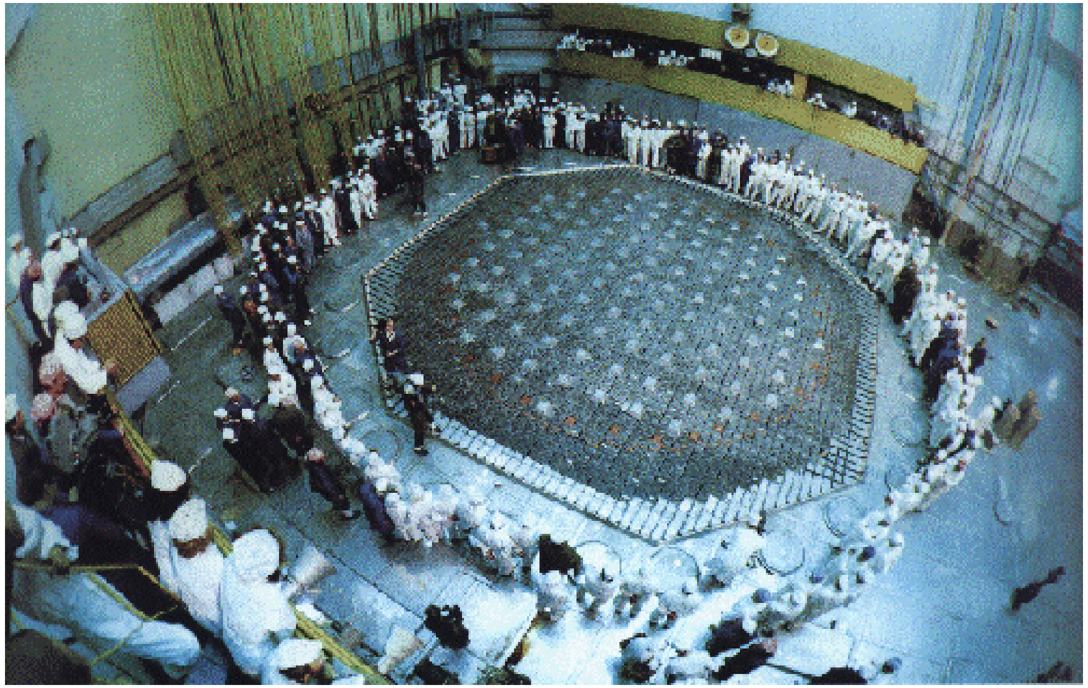
➔ So, when your colleagues are showered with money for doing "quantum physics", you should start a revolution and claim your share!

Q: why we cannot get very substantial funds for quantum communications?

A: because the quantum efficiency to detect neutrinos is essentially 0

In our language: the mean free path of neutrinos from a reactor in lead is ~ 0.3 light years !

A big nuclear reactor makes $6 \cdot 10^{20}$ ν/s:
at 20 meter distance (just outside the containment building) only one neutrino every 3 sec interacts with our body!



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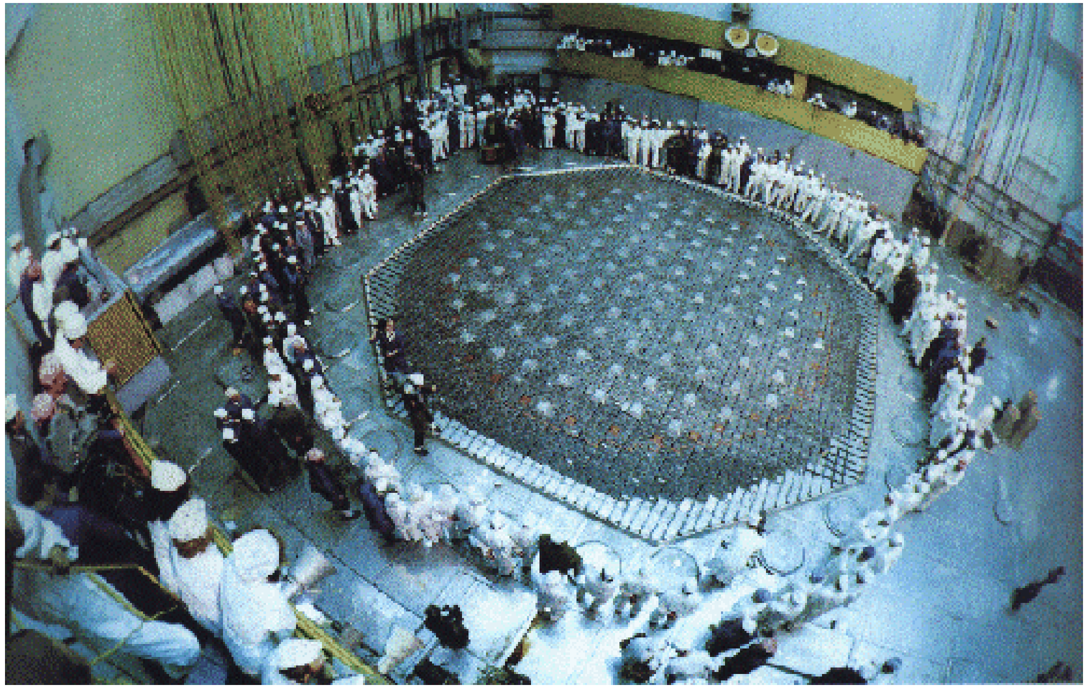

This has been known for a long time:
"… this implies that one evidently never will be able to detect Neutrinos."
(Bethe & Peierls 1934)

The neutrinos are then detected via weak interactions so that we need to find again the composition in terms of ν_e, ν_μ, ν_τ

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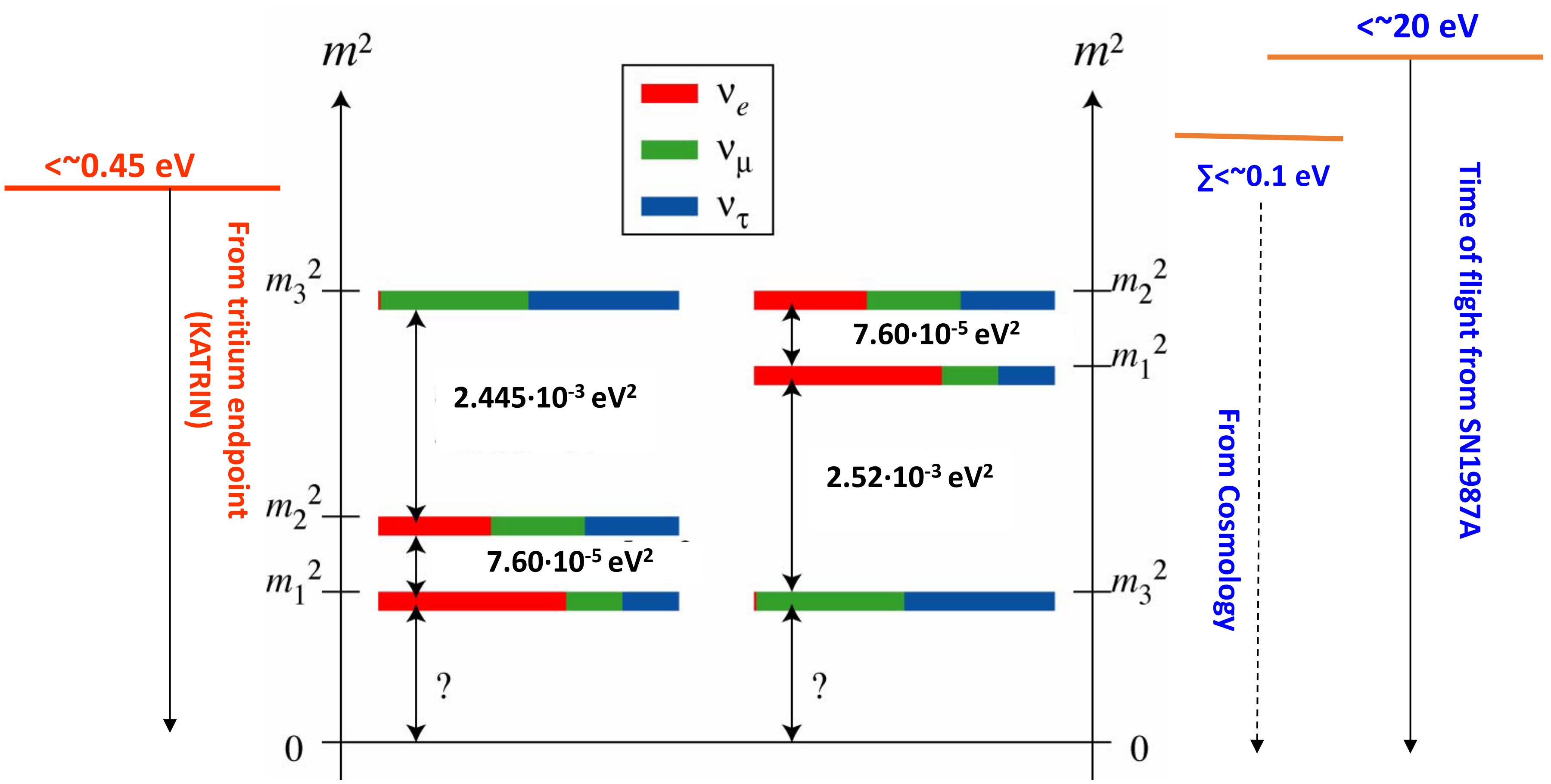
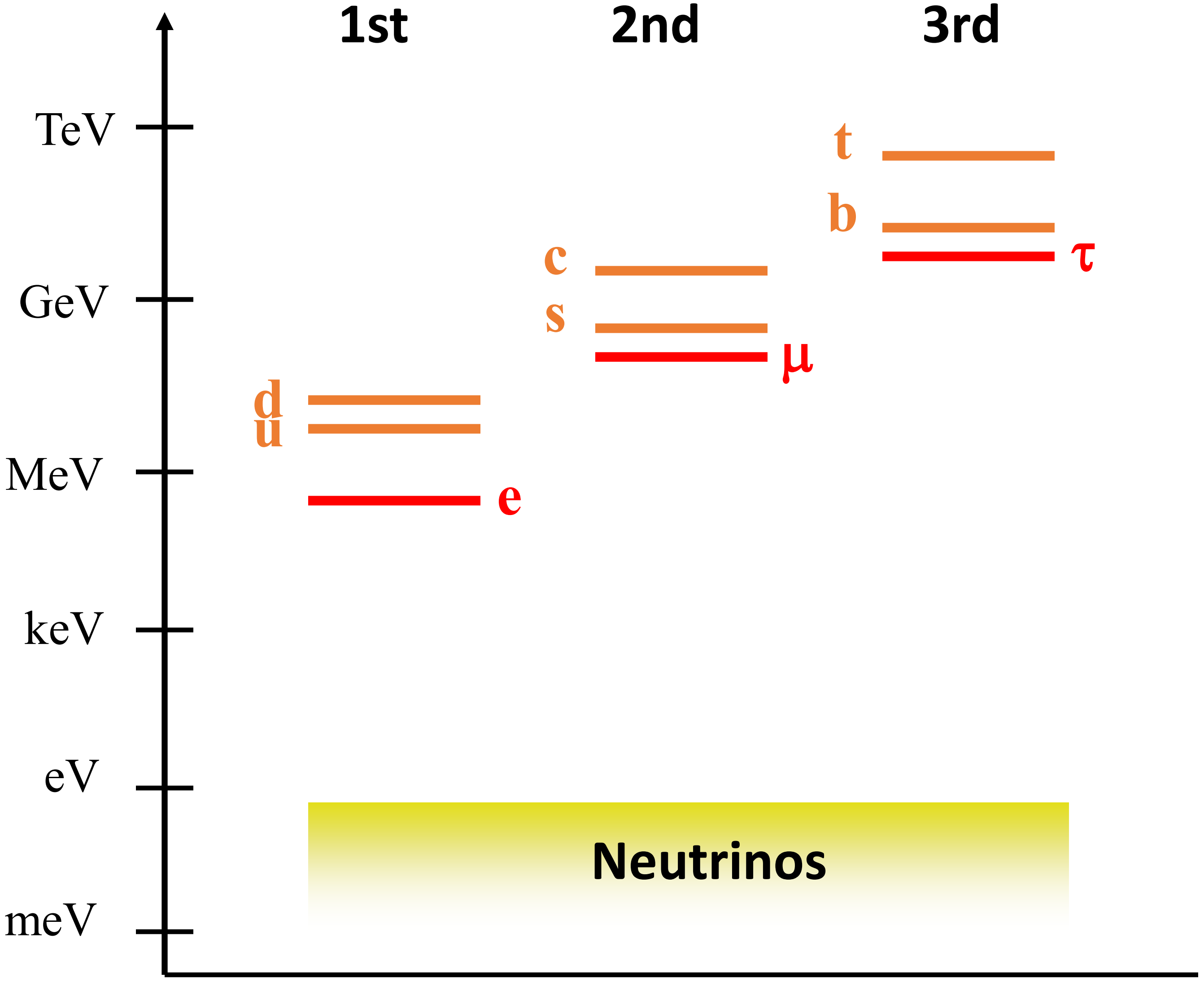
It can ONLY happen if the mass is non-0

Our knowledge of the ν mass pattern



From PDGonline, Jun 2026

Fermion mass spectrum



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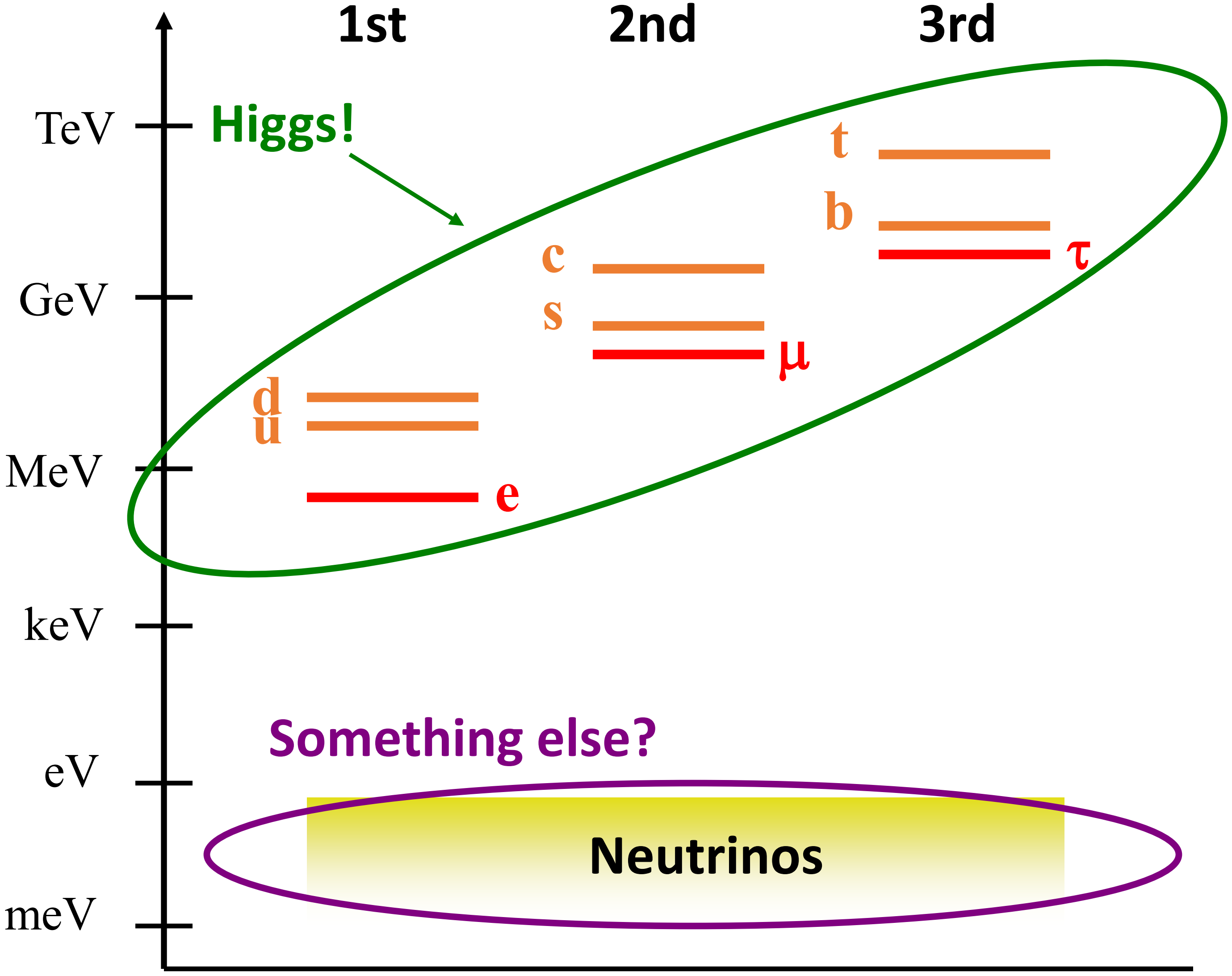


Neutrinos have other peculiarities:
They are the only electrically neutral fermions

Generation

Charge	1st	2nd	3rd
1	e^+	μ^+	τ^+
2/3	u	c	t
1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
0	ν_e	ν_μ	ν_τ
-1/3	d	s	b
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
-1	e^-	μ^-	τ^-

Neutrinos do not carry charge
What about lepton number?

Could it be that the mass and charge peculiarities are somehow related?

Say that for neutrinos $\overline{\nu} = \nu$, since they have no charge…

But… isn't there a lepton number to conserve?

No worries: lepton number conservation is not as "serious" as –say- energy conservation.

Lepton number conservation is just an empirical notion.

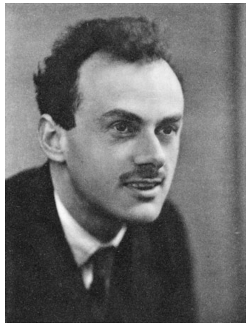
Basically, lepton number is conserved "because", experimentally, $\bar{\nu} \neq \nu$.
But, in the neutral case, the distinction could derive from the different helicity states.

We have two possible ways to describe neutrinos:

"Dirac" neutrinos

(some "redundant" information but the "good feeling" of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$



"Majorana" neutrinos

(more efficient description, no lepton number conservation, new paradigm…)

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

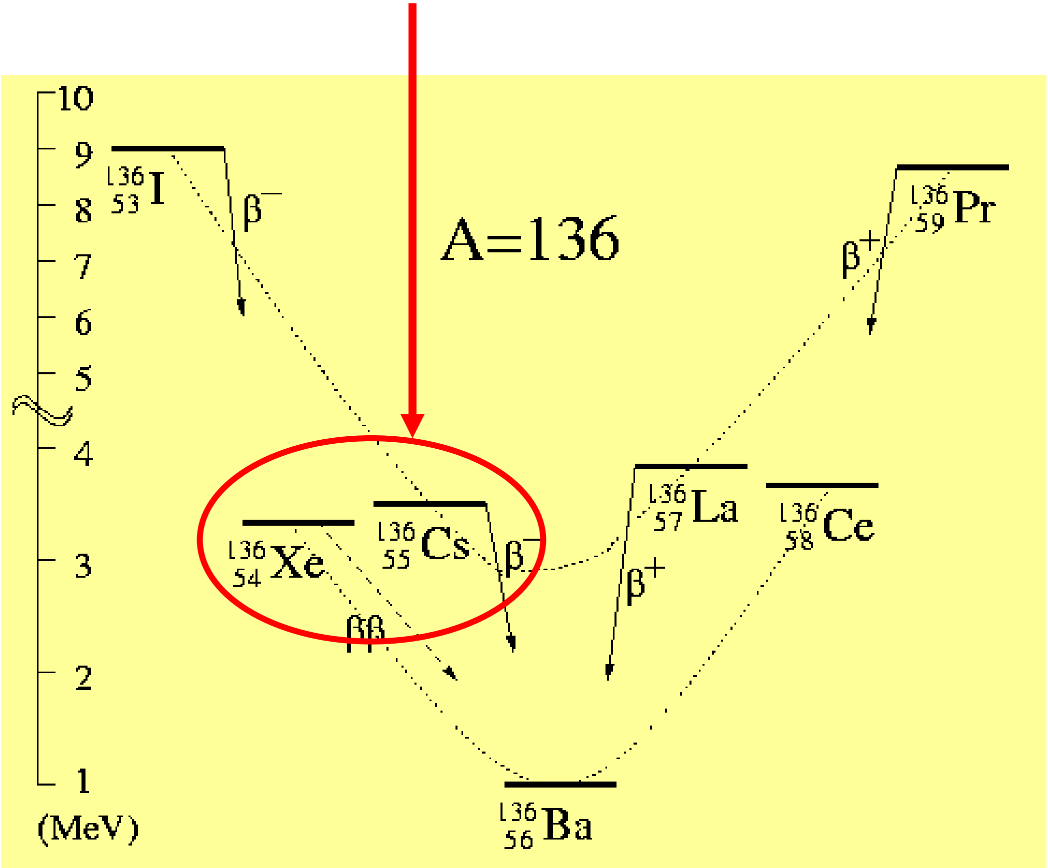
Which way Nature has chosen to proceed is an experimental question

However, the two descriptions are distinguishable only if $m_\nu \neq 0$

(and the observable difference → 0 for m_ν → 0)

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



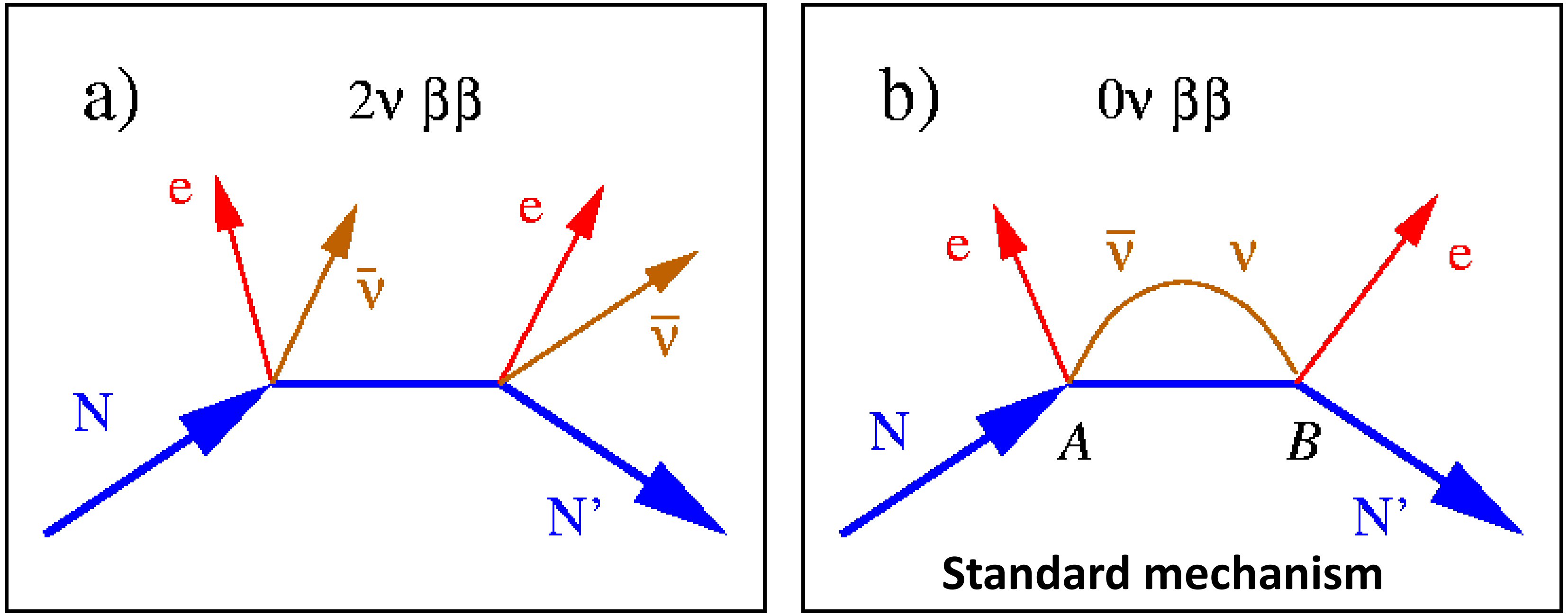
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

2ν mode:
a conventional
2^{nd} order process
in nuclear physics

0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$
$\nu = \bar{\nu}$
$|\Delta L|=2$
$|\Delta(B-L)|=2$



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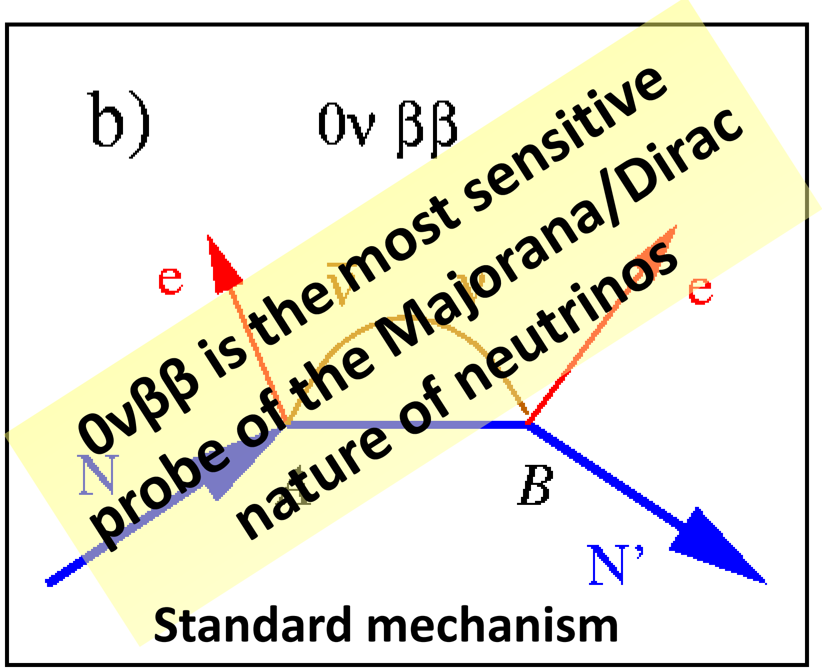
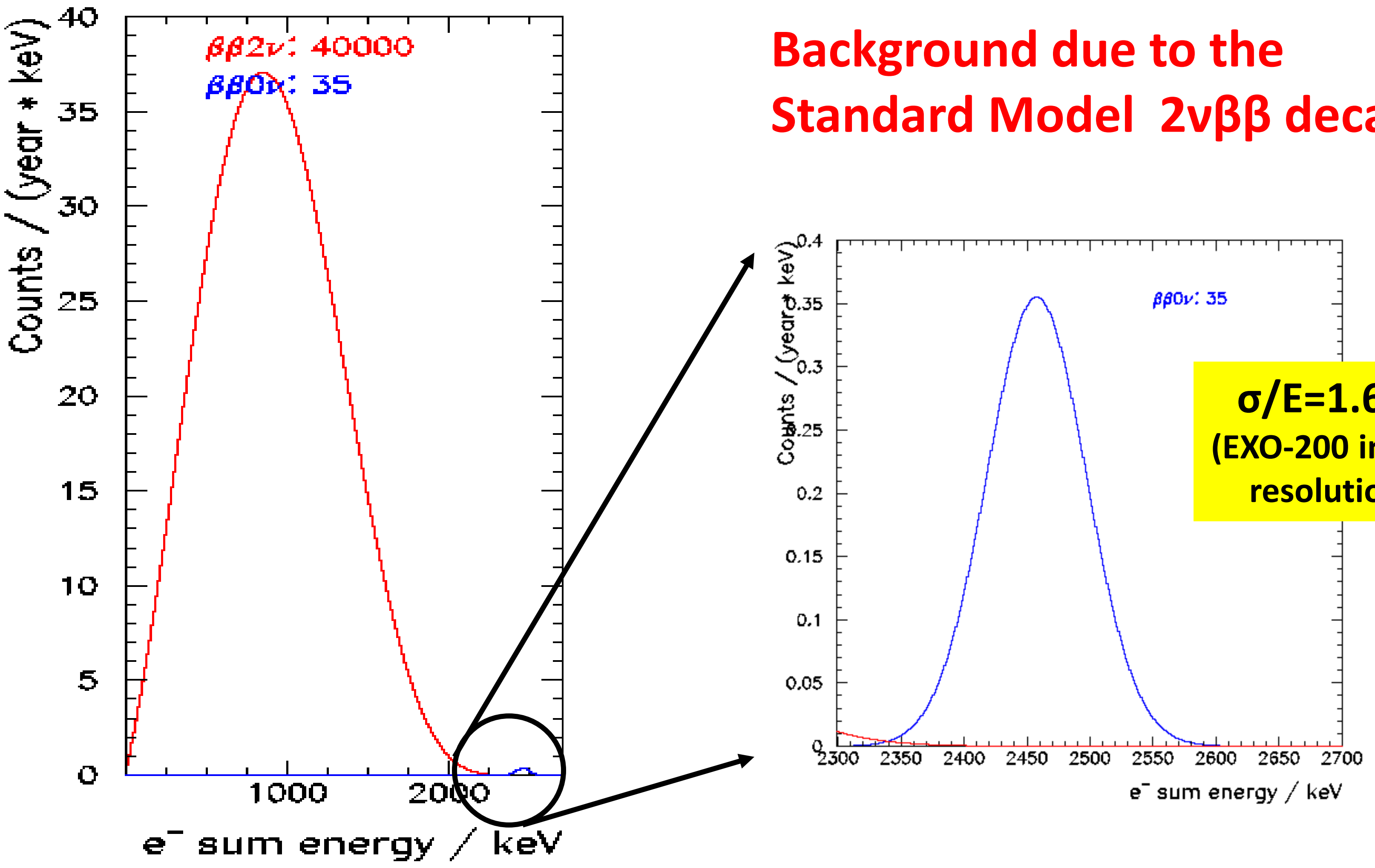


Background due to the Standard Model 2νββ decay



σ/E=1.6%
(EXO-200 initial resolution)

The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize other backgrounds

The idea of double-beta decay is almost as old as neutrinos themselves:

The possibility of neutrinos-less decay
was first discussed in 1937:

E. Majorana, Nuovo Cimento 14 (1937) 171
G. Racah, Nuovo Cimento 14 (1937) 322

Even earlier the study of nuclear structure led to the conclusion that the 2 neutrino mode would have half lives in excess of 10^{20} years

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

Note that along with the double β⁻ decay

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+2}N' + e^- + e^- $$

there is also a β⁺ mode. In practice this would also appear as single or double electron capture

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z-2}N' + e^+ + e^+ $$

$$ {}^{A}_{Z}N + e^- \rightarrow {}^{A}_{Z-2}N' + e^+ $$

$$ {}^{A}_{Z}N + e^- + e^- \rightarrow {}^{A}_{Z-2}N' $$

All these processes are phase-space suppressed with respect to the β⁻ case and isotope fractions low in natural mix: usually not considered

Of course, these processes exist also in the SM version with 2ν.

Conclusion #1:

The finite neutrino mass from oscillations means that, if neutrinos are Majorana particles, $0\nu\beta\beta$ decay is observable.

Conclusion #2:

The observation of the $0\nu\beta\beta$ decay, i.e. the measurement of a finite half-life would be a great discovery with no other qualification.

This is why we are doing those experiments!

In fact, there is a *theorem*:

"$0\nu\beta\beta$ decay always implies new physics"

There is no scenario in which observing $0\nu\beta\beta$ decay would not be a great discovery

- ➔ **Majorana neutrinos**
- ➔ **Lepton number violation**
- ➔ **Probe new mass mechanism up to the GUT scale**
- ➔ **Probe key ingredient in generating cosmic baryon asymmetry**

Conclusion #3:
A healthy neutrinoless double-beta decay program requires several isotopes.

This is because:

- *Different isotopes correspond to vastly different experimental techniques*
- *Because of the uncertainties in Nuclear Matrix Elements any given isotope could come with unknown liabilities*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*
- *2 neutrino background is different for various isotopes*
- *There could be unknown γ transitions and a line observed at the "end point" in one isotope does not necessarily imply the $0\nu\beta\beta$ decay discovery (although in modern detectors, this is somewhat less of an issue)*

These principles are well recognized by funding agencies, until... they were not.

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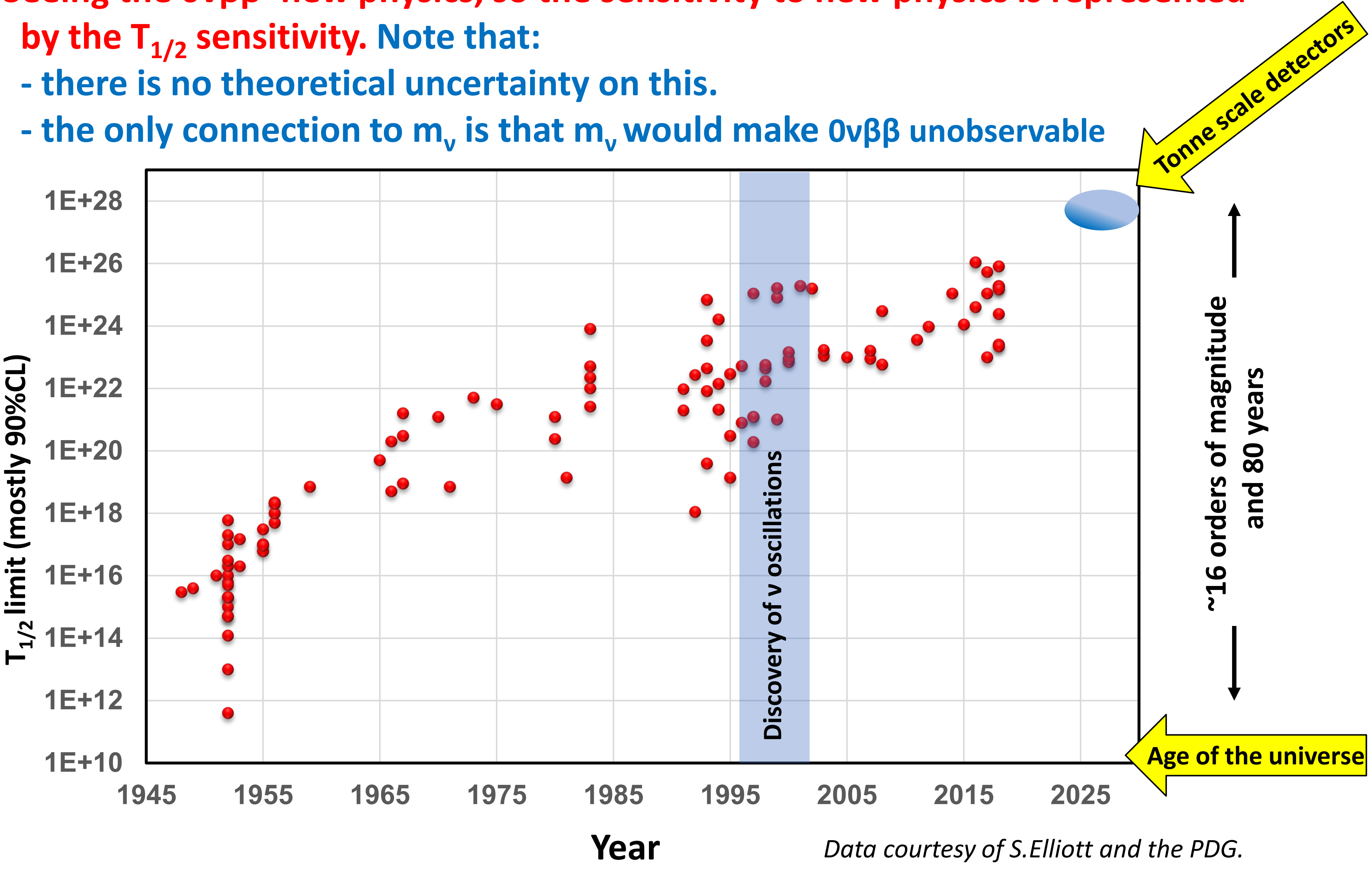
Seeing the 0νββ=new physics, so the sensitivity to new physics is represented by the $T_{1/2}$ sensitivity. **Note that:**

- **there is no theoretical uncertainty on this.**
- **the only connection to m_ν is that m_ν would make 0νββ unobservable**



Data courtesy of S.Elliott and the PDG. Not all results are necessarily shown.

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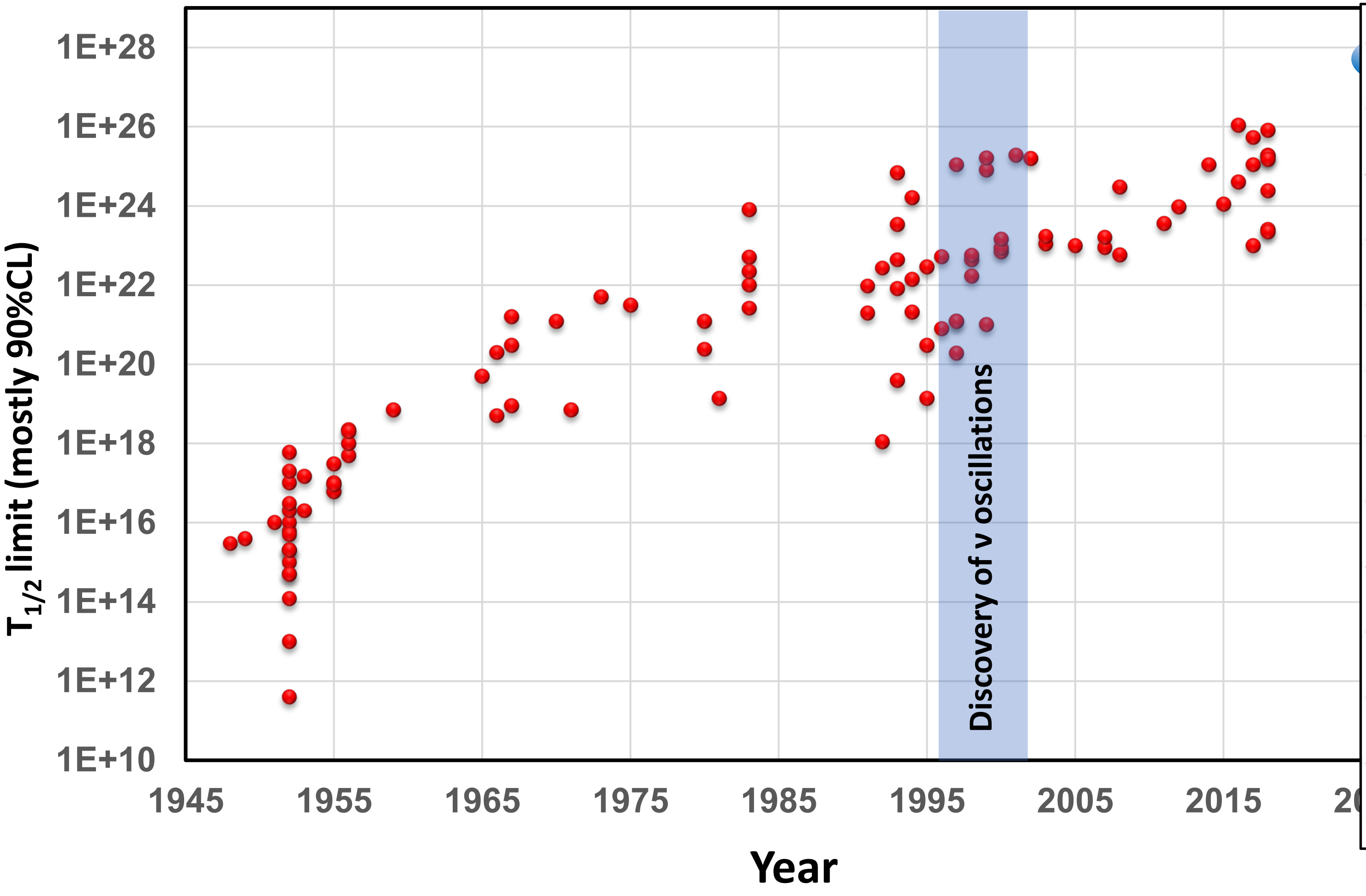
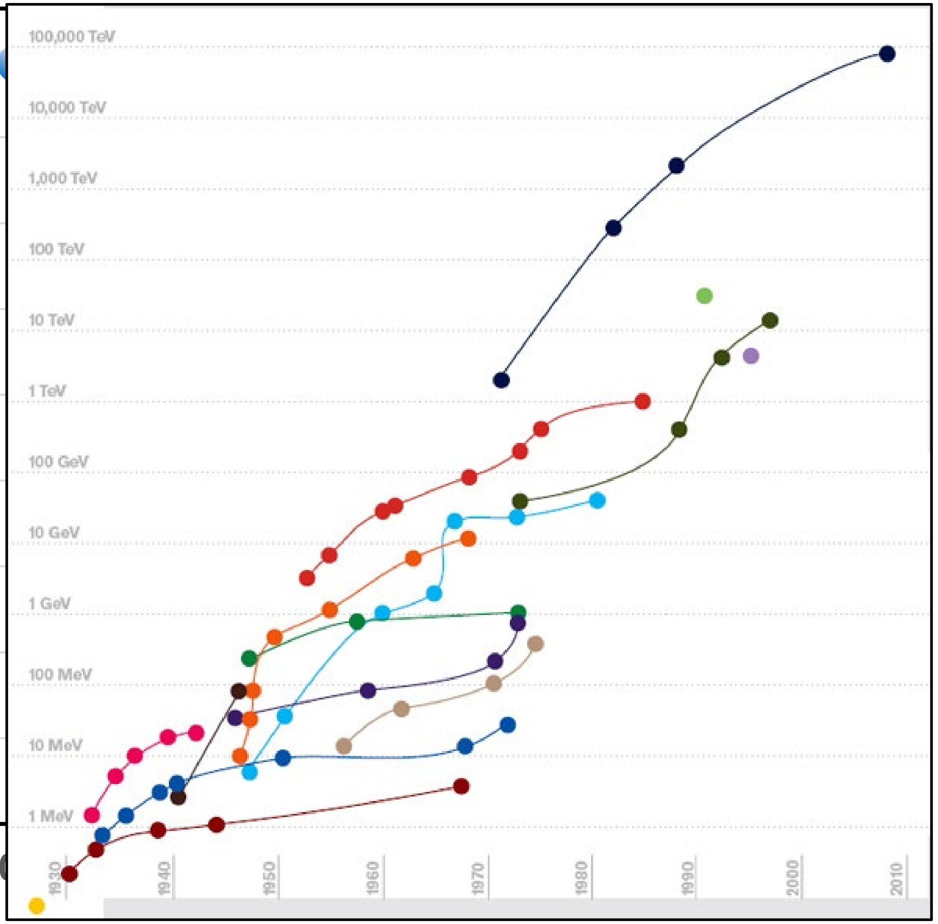
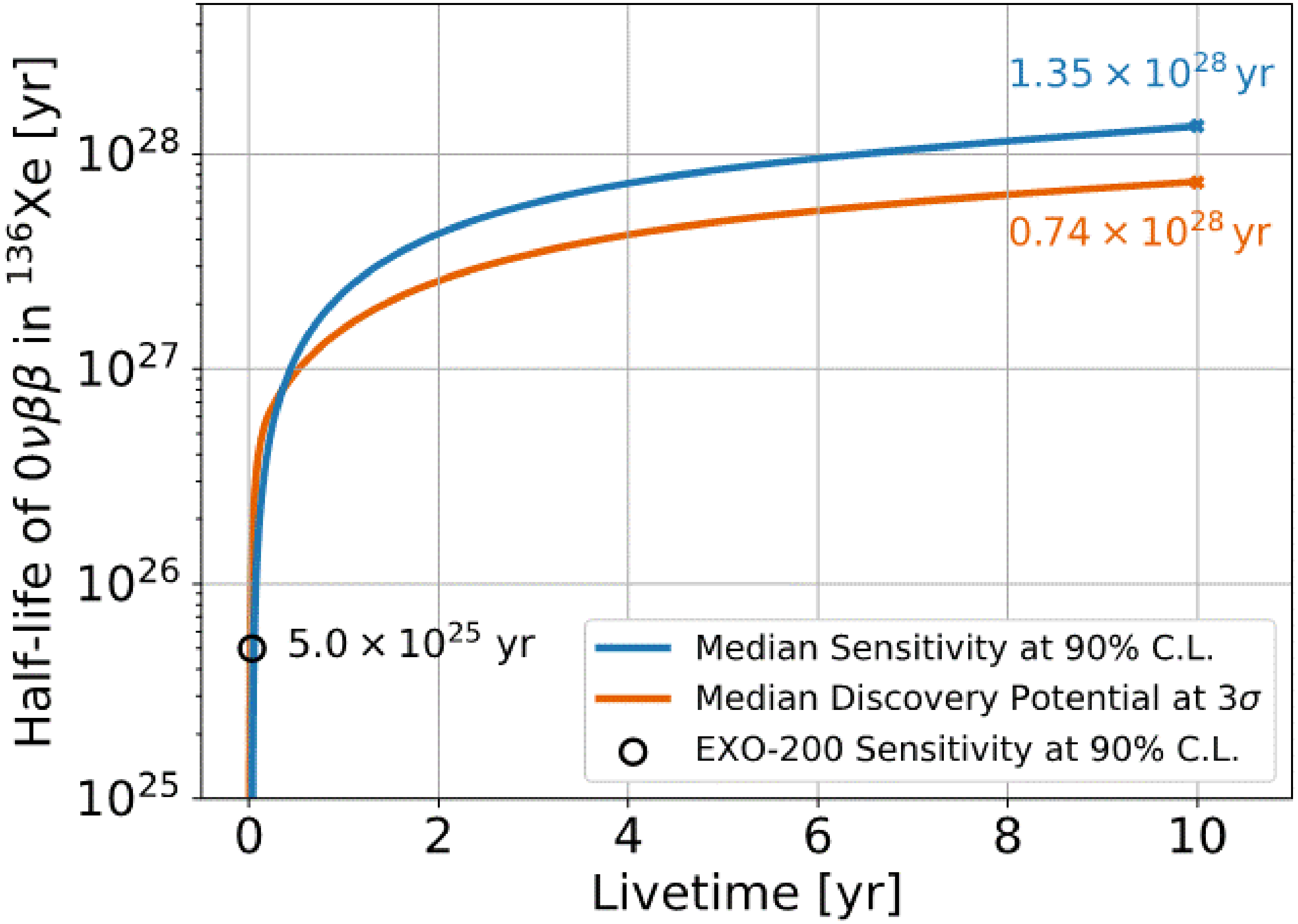


For accelerators this plot has a name: "Livingston plot"
Here the vertical scale for colliders is the lab energy of a particle hitting a proton in the lab frame that produces the same center-of-mass energy of the collider.
Different colors correspond to different technologies.



(from Symmetry Magazine)

Example of projected sensitivity for a modern experiment (nEXO)



Amedeo Avogadro

Note that we owe the spectacular 10^{28} half life sensitivity to Mr. Avogadro, so there is no silver bullet to improve it.

This has two manifestations, contrasting the case of accelerators:

- **There is no such thing as "a new technology" that suddenly permits a drastically better sensitivity reach (essentially, this is because of the density of matter, more later)**
- **Once data taking starts, most of the sensitivity is reached rapidly. This is a property of statistics.**

Yet, the sensitivity in terms of half-life has an empirical flavor that is not satisfying:

One would like to express the sensitivity in terms of some deeper parameter of the theory.
This is not only matter of intellectual satisfaction, because it is also the only practical way of comparing physics reach from experiments using different isotopes.

There are two problems with this:

1) We do not know which kind of new physics may be responsible for a certain half-life we may eventually observe.
2) In any case, there is complicated nuclear physics between $T_{1/2}$ and the particle physics. If you are not a theorist, you can very naively think of this as describing the overlap of nucleon wavefunctions due to nuclear structure.

So, what to do? For 1) there is not much one can do, but chose one model and use it (or maybe show the reach for different models). Usually the "light neutrino exchange" model is used, with the sensitivity expressed in terms of "Majorana neutrino mass", but this is really only one possibility out of many!
For 2) the idea is to do the best possible nuclear structure calculation(s) and try estimating their uncertainties. A number of auxiliary experiments may help estimating such uncertainties.

Enter nuclear structure!

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

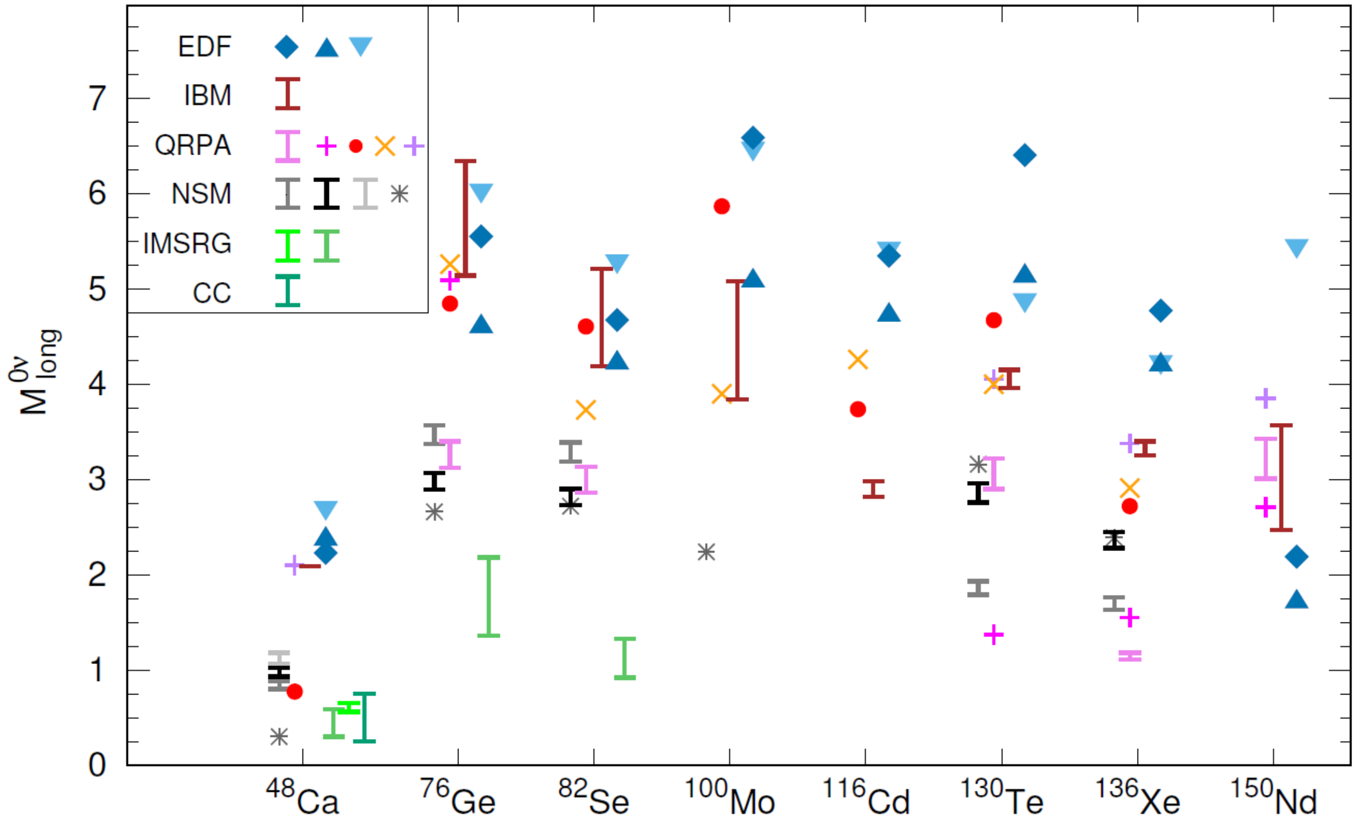
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

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

is the effective Majorana ν mass (ε_i = ±1 if CP is conserved)

Nuclear Matrix elements are still rather different, for different calculations.

Below is the case, more commonly calculated, of light neutrino exchange.

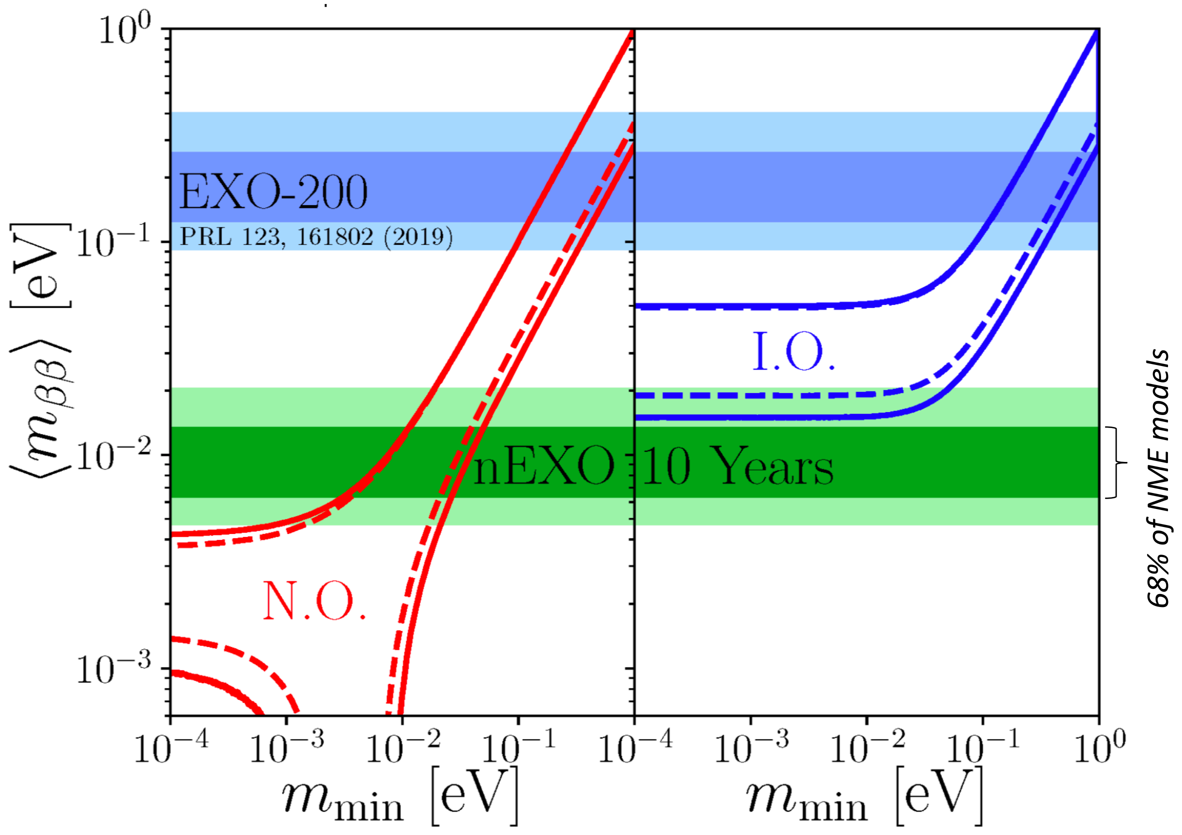


In fact, this is not even the entire story, as there are questions on what value of g_A, the axial coupling constant, should be used. This is probably kind-of-common for all NMEs and usually not shown.
Although there is recent progress in understanding these issues.

M.Agostini et al., arXiv:2202.01787, 2022 (to be also consulted for the references to the individual calculations)
See also J.Engel & J.Menendez, Rep. Prog. Phys. 80, 046301.

With all the above caveats the we can express the sensitivity to Majorana Mass for light neutrino exchange

Allowed parameter space and nEXO exclusion sensitivity (90% CL):

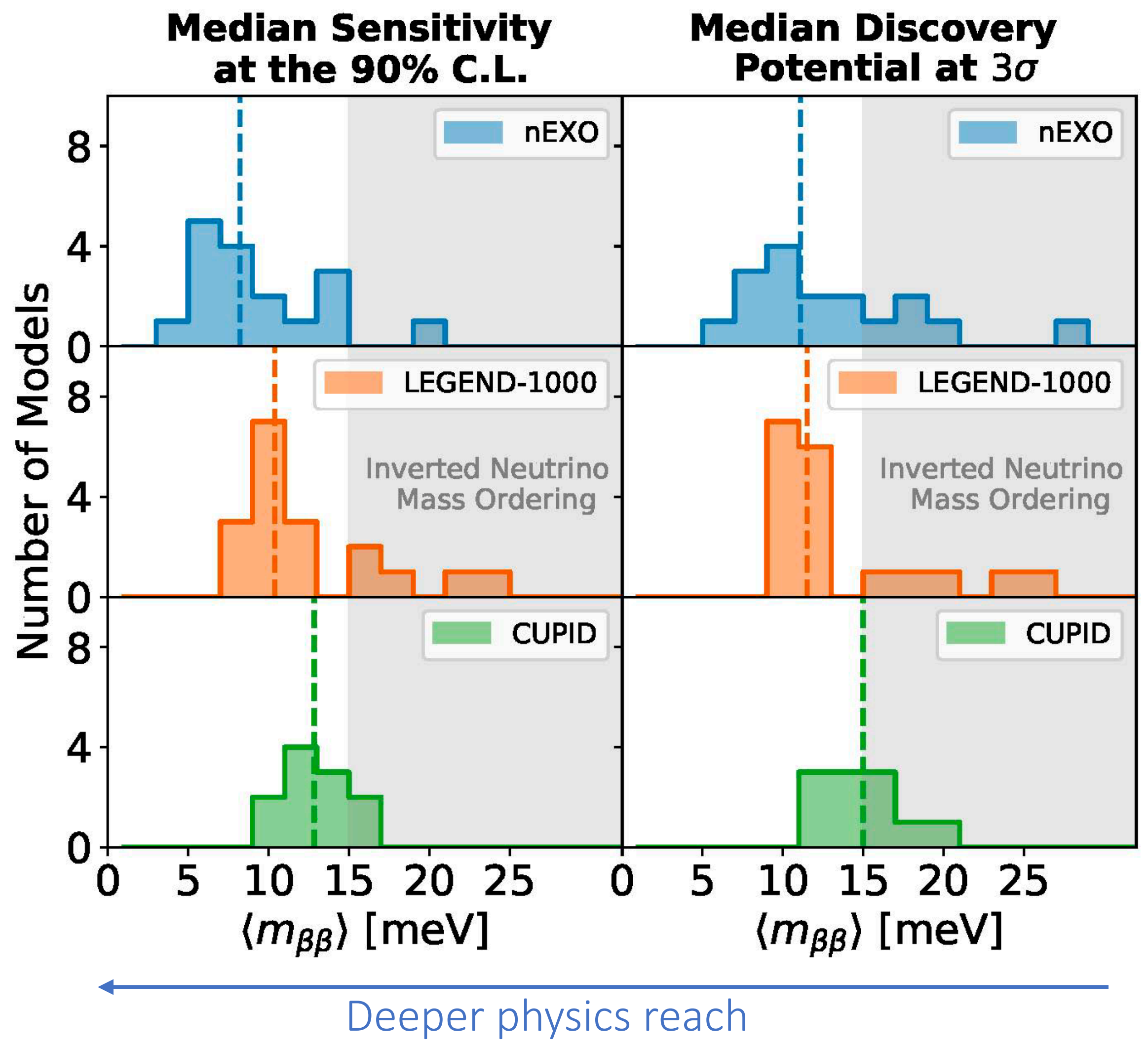


Here the extent of the darker bands contains 68% of the NMEs (but not the uncertainty from g_A).

The lighter bands also contains uncertainties from the oscillation measurements.

We are ready to compare experiments based on different isotopes

(shown here are some examples of fully designed experiments)



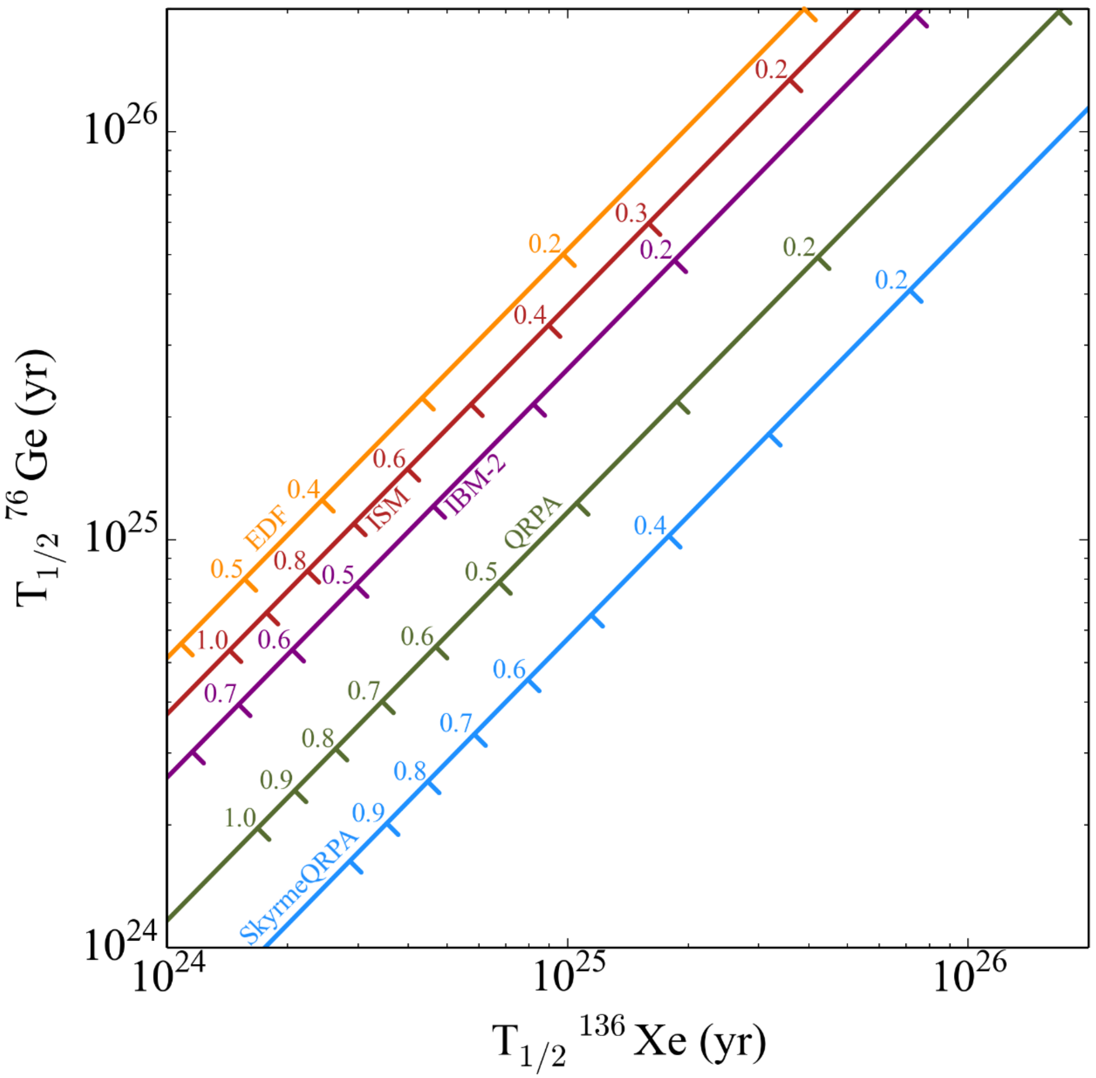
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ values used [x10^{28} yr]:

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.)
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.)
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.)

A useful way to relate different isotopes and compare results

(assumes the standard mechanism, this is an example, not all NMEs are shown)



EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

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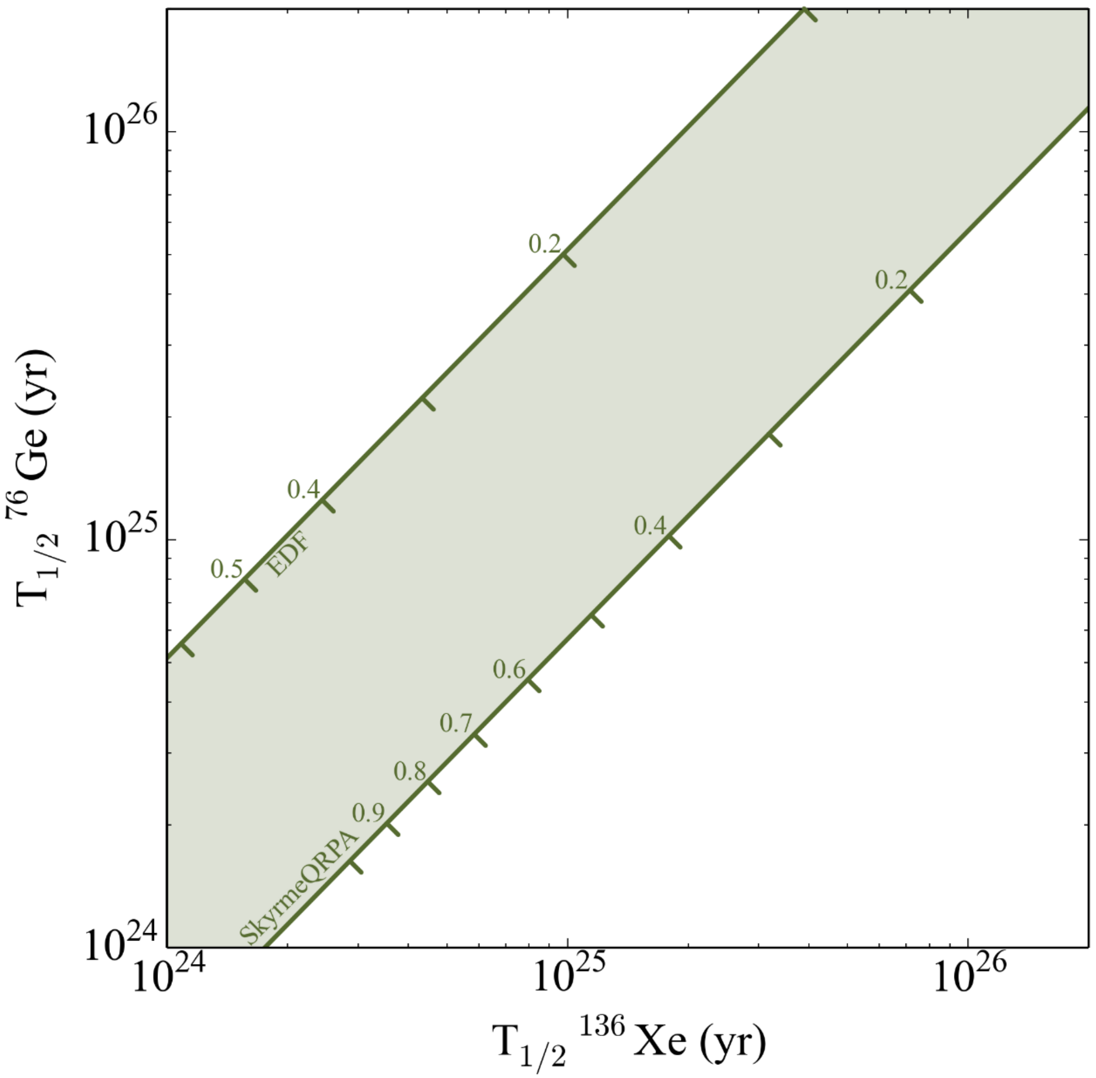
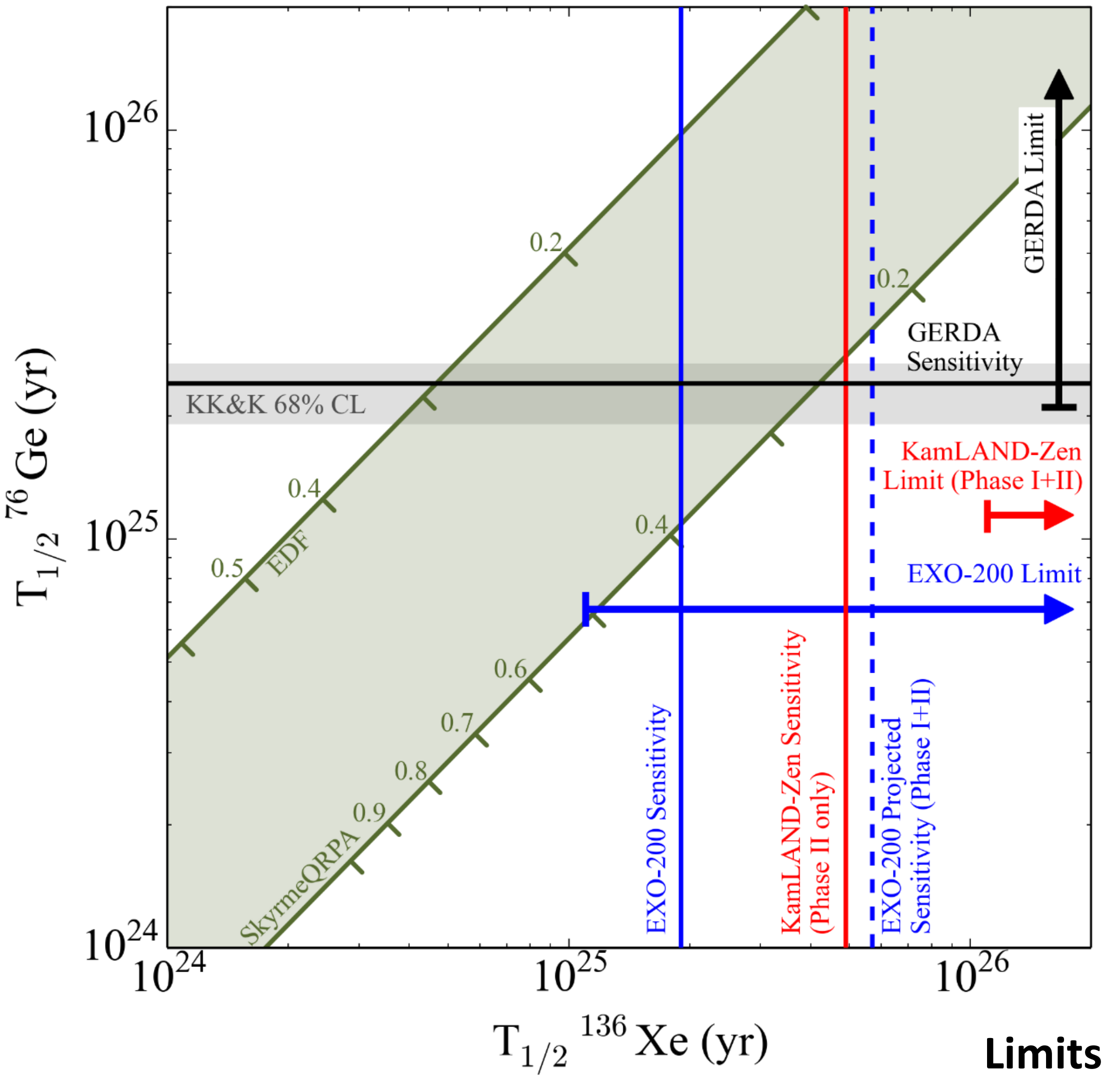


There are more/better results by now (both from theory and experiments);
this old plot is just to illustrate the idea.



GERDA: M.Agostini et al., Phys. Rev. Lett. 111 (2013) 122503

KLZ: A.Gando et al., arXiv:1605.02889 (May 2016)

EXO-200: J.B.Albert et al., Nature 510 (2014) 299

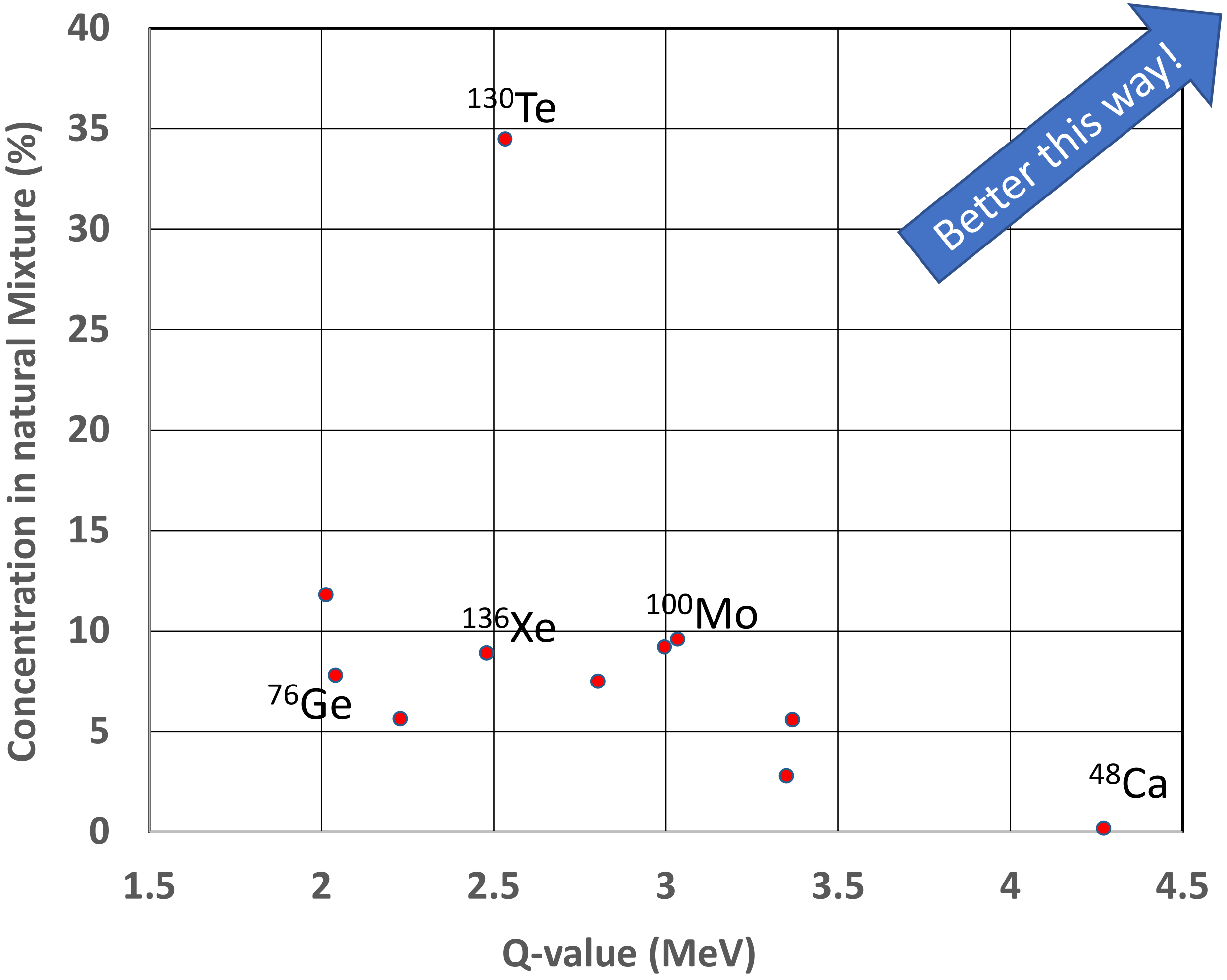
Limits are 90% CL

Q: How to choose an isotope for $0\nu\beta\beta$ decay?

Easy: select an isotope with large natural abundance and large Q-value

Large Q-value is good in two ways:

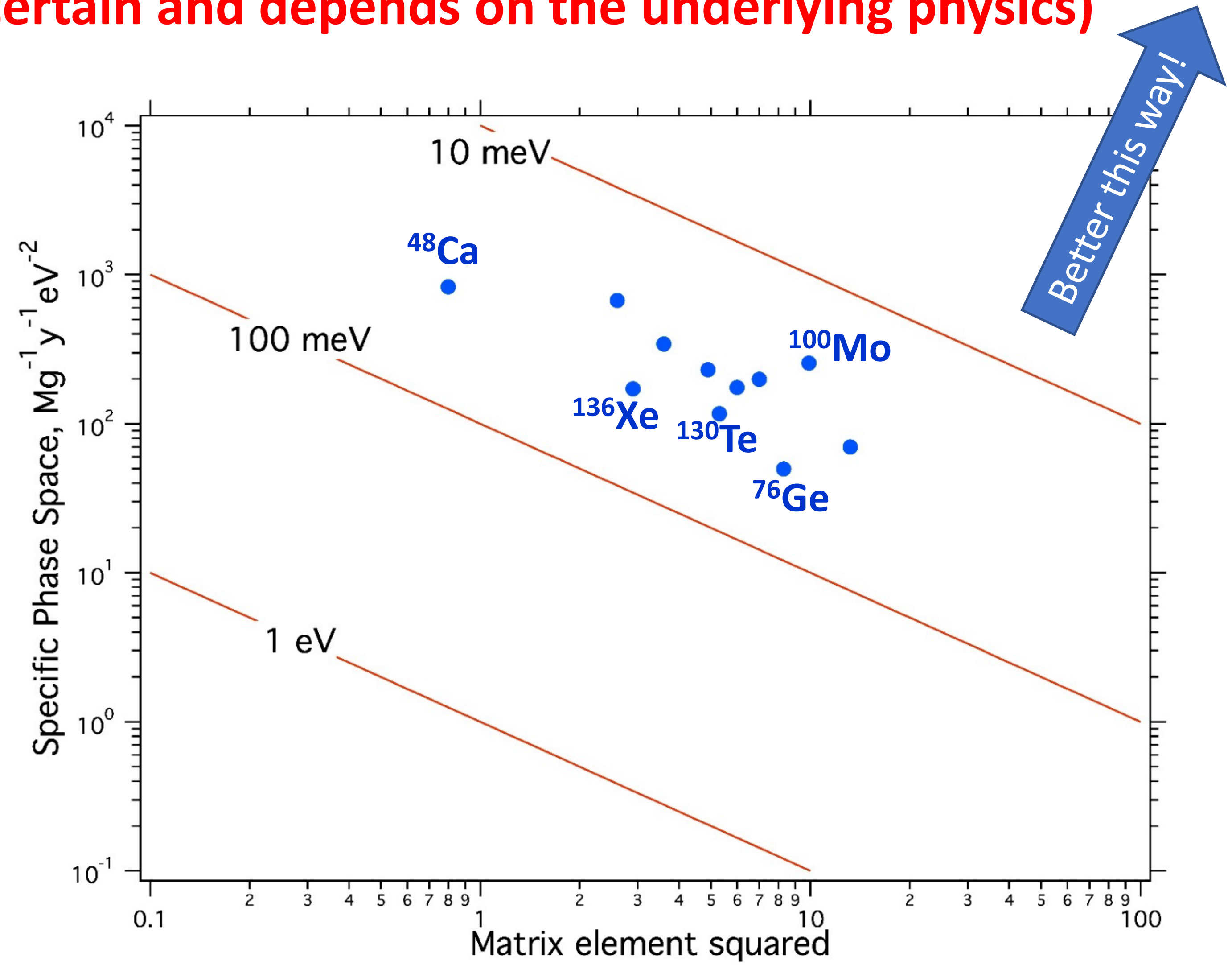
1) **provides larger phase space for the decay and**
2) **moves the signal away from natural radioactivity background**



Candidate 0νββ isotopes with Q-value > 2MeV

What about phase space and predicted Nuclear Matrix Element?
(which, again, is uncertain and depends on the underlying physics)

Note that there is an "empirical" anticorrelation between phase space and NME.



R.G.H. Robertson, MPL A 28 (2013) 1350021

Unfortunately, there is no a-priori magical isotope and one can really only answer the question bringing in detector technology, which is intimately connected to the choice of isotope.

Of course, the main experimental challenge is the small size of the signal, that is, the need for exceedingly small background.

This can be benchmarked by providing the signal count implied by different half lives

$T^{1/2}$ (yr)	Resulting signal (counts $tonne^{-1}$ yr^{-1})
10^{26}	≈ 50
10^{27}	≈ 5
10^{28}	≈ 0.5

The name of the game is then to reduce the background as much as possible, while maintaining good signal efficiency.

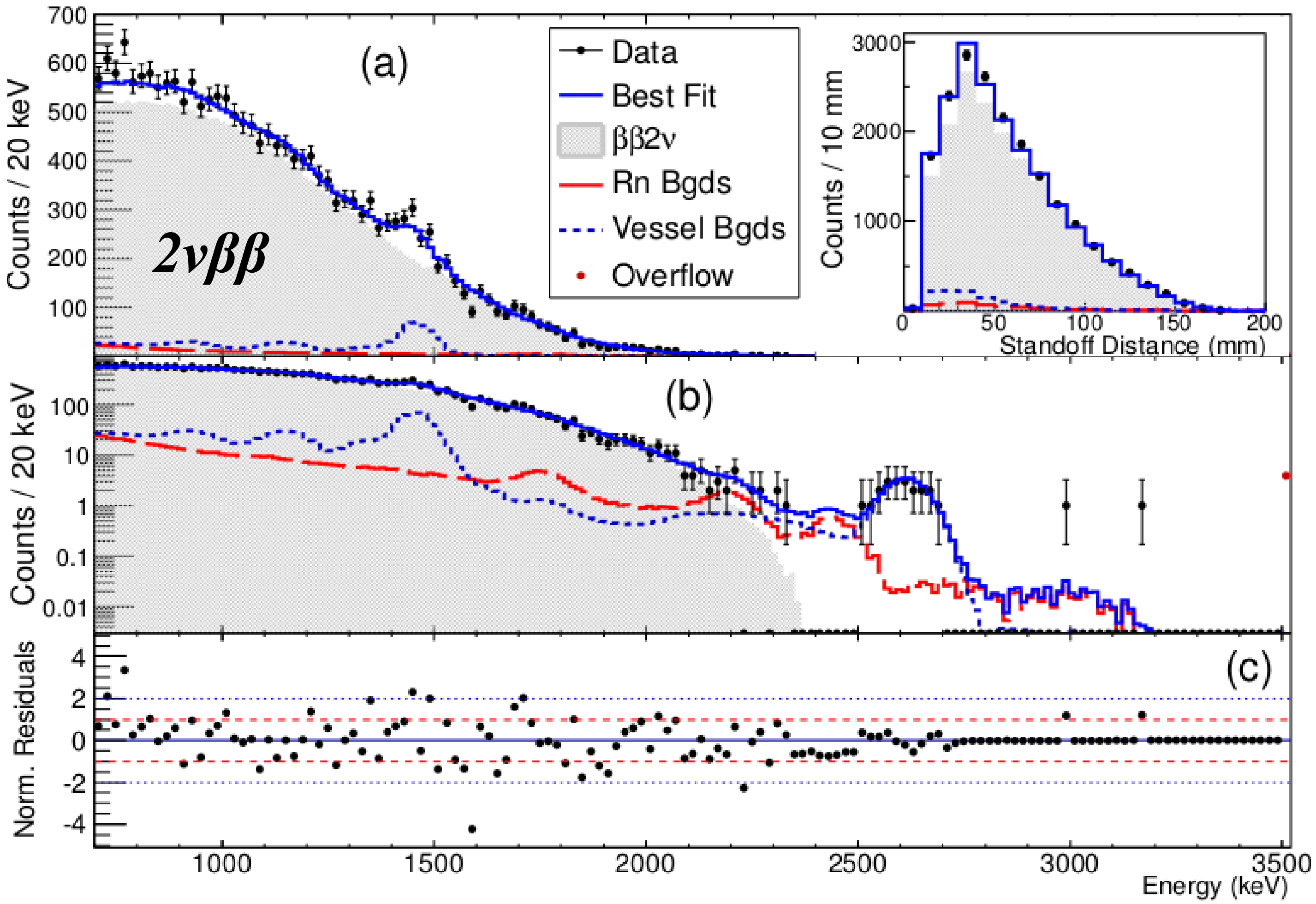
If background needs to be subtracted, its fluctuations make the sensitivity scale with $\sqrt{Isotope\ Mass \times livetime}$ instead of $Isotope\ Mass \times livetime$ for the case of no background (or background that is infinitely well measured).

A few comments on the Standard Model decays

$2\nu\beta\beta$ decay: ***yesterday's signal is tomorrow's background.***

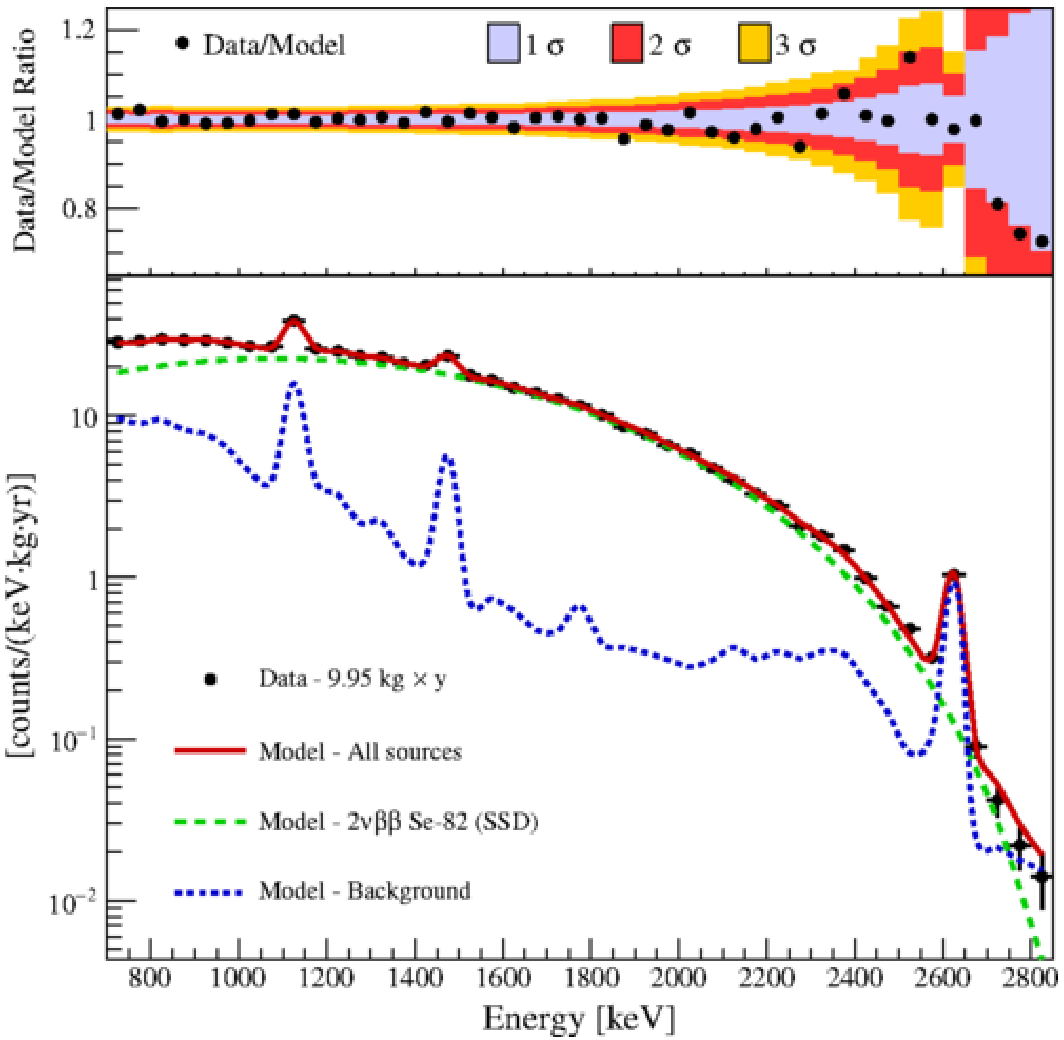
In "discovery mode" the $2\nu\beta\beta$ decay is really difficult, because it has no spectral features. However, modern detectors have tremendous statistics and small and well-understood backgrounds, so the decay dominates the count rate!

^{136}Xe



J.Albert *et al.* (EXO-200)
Phys Rev C 89 (2014) 015502

…or, for ^{82}Se,



O. Azzolini *et al.* (CUPID-0)
Phys. Rev. Lett. 123 (2019) 262501

Remarkably, the half-life into this mode (up to ≈10^{21} yr*), in many cases is known to better than 2%! Precision physics!

	Nuclide	$T_{1/2}$ (10^{21}yr)	Rel. Uncertainty (%)	Experiment	Published yr
2νββ	^{76}Ge	$2.022 \pm 0.018 \pm 0.038$	2.1	GERDA	2023
	^{82}Se	$(8.69 \pm 0.05^{+0.09}_{-0.06}) \cdot 10^{-2}$	1.2	CUPID-0	2023
	^{100}Mo	$(7.07 \pm 0.02 \pm 0.11) \cdot 10^{-3}$	1.6	CUPID-Mo	2023
	^{130}Te	$(9.32^{+0.06}_{-0.04} \pm 0.07) \cdot 10^{-1}$	1.0	CUORE	2025
	^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	2.8	EXO-200	2014
2ν2EC	^{124}Xe	$10.9 \pm 1.4 \pm 0.5$	13.6	LZ	2024

*** In "natural units" this is 10^{11} the age of the Universe!**
(I will continue using these natural units on and off).