Neutrinoless double beta decay: from rates to Majorana masses

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New era of neutrino physics

1. **Atmospheric neutrino oscillations**

(in particular zenith angle dependence of the muon neutrino flux)

2. **Solar neutrino deficit**

(in particular the difference in neutrino fluxes deduced from the charged and neutral current reaction rates)

3. **KamLAND**

(reactor $\overline{\nu_e}$ *disappearance, oscillations seen with the terrestrial sources)*

4. **LSND oscillation observations**

(unconfirmed, but soon to be checked; if correct all bets are off)

Consequences:

- At least some neutrinos are massive.

(lower limits are 50 and 10 meV)

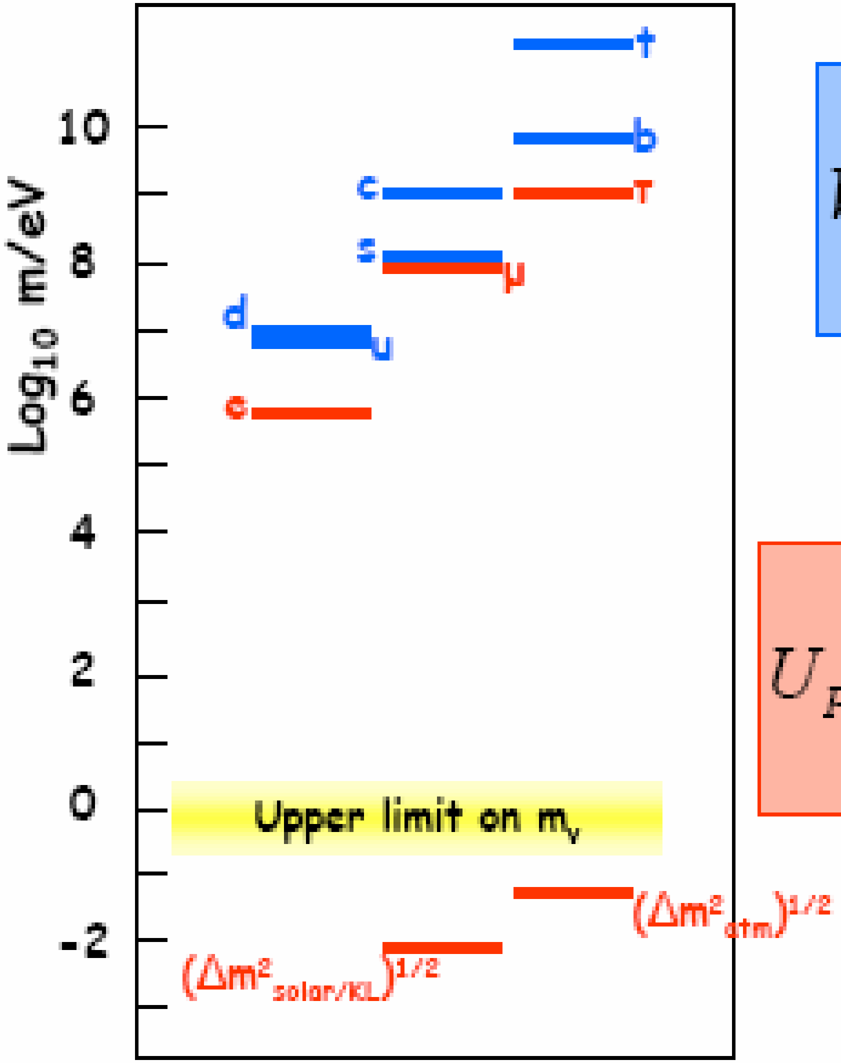
- Mixing exists

(two mixing angles are large, one is small)

- But we do not know the absolute mass scale
- We do not know the behavior under charge conjugation

$0\nu\beta\beta$ might help with the answers

So the neutrino sector is really strange !

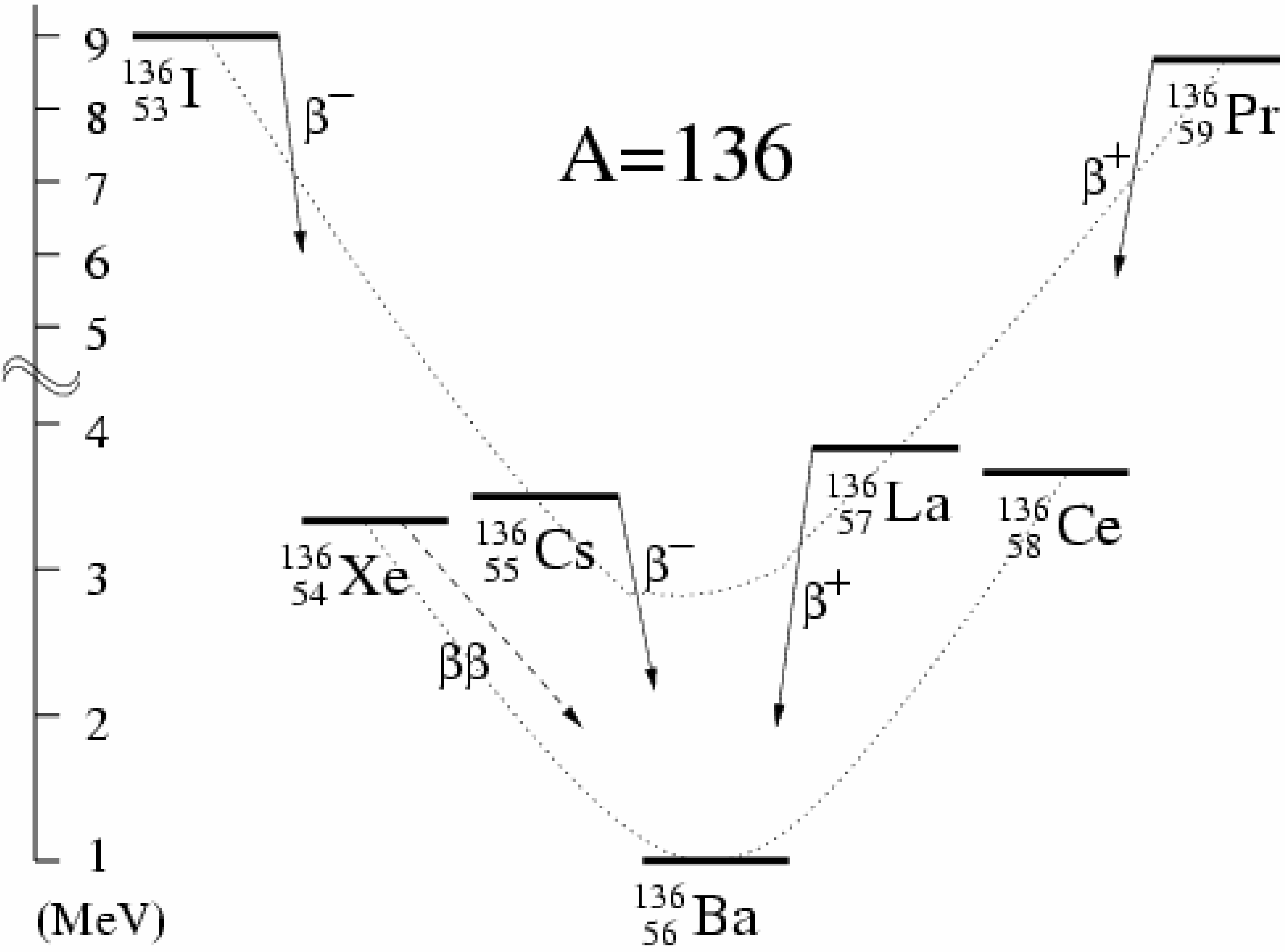


$$V_{CKM} \cong \begin{pmatrix} 0.97 & 0.22 & 0.00 \\ 0.22 & 1.00 & 0.04 \\ 0.01 & 0.04 & 1.00 \end{pmatrix}$$

Adapted from PDG 2002

$$U_{PMNS} \cong \begin{pmatrix} 0.84 & 0.54 & 0.1 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}$$

(entries evaluated for $U_{e3} = 0.1$, near the middle of allowed range)


A=136
9
8
7
6
5
4
3
2
1
(MeV)
$^{136}_{53}$I
β^-
$^{136}_{54}$Xe
$^{136}_{55}$Cs
β^-
$\beta\beta$
$^{136}_{56}$Ba
$^{136}_{57}$La
β^+
$^{136}_{58}$Ce
$^{136}_{59}$Pr
β^+

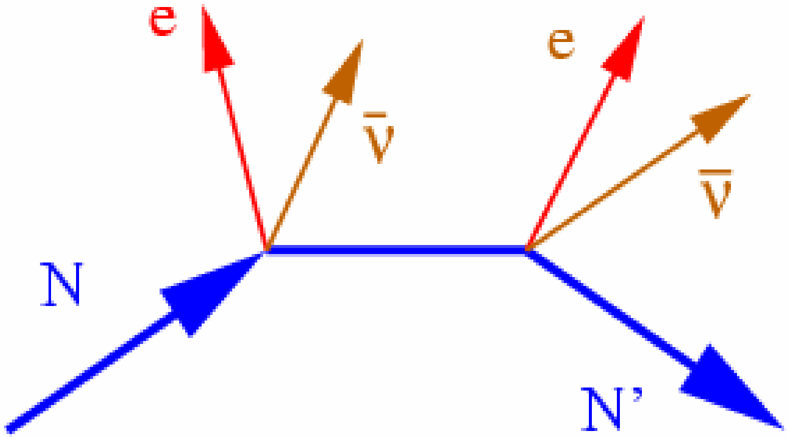
Candidate Nuclei for Double Beta Decay

	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

Issues include : Q value, abundance, ease of purification (chemical and isotopic), radioactivity (incl. cosmogenesis), & experimental ease of use.

Most sensitive neutrino mass measurements can be obtained from double-beta decay

$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



$0\nu\ \beta\beta$ decay: a hypothetical process

$\rightarrow m_\nu \neq 0$

$\rightarrow \bar{\nu} = \nu$

since helicity has to "flip"

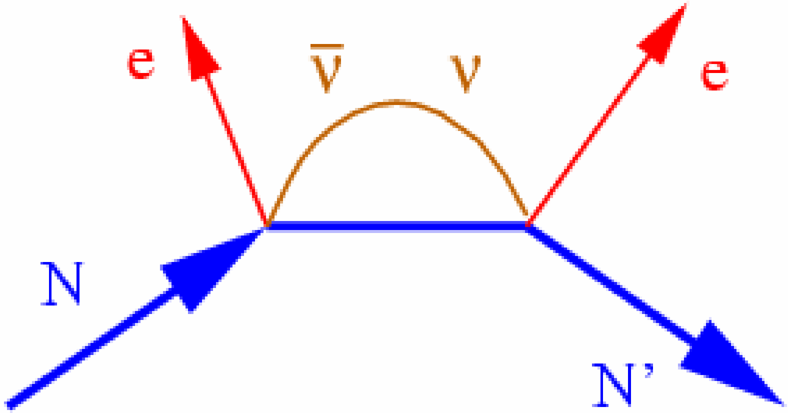


FIG. 1. How to separate the 2ν and 0ν decays? Dotted line is the sum electron spectrum for the 2ν decay, full line is for the 0ν decay. 5% resolution is assumed. The ratio of rates is 10^2, and 10^6 (goal) in the insert.

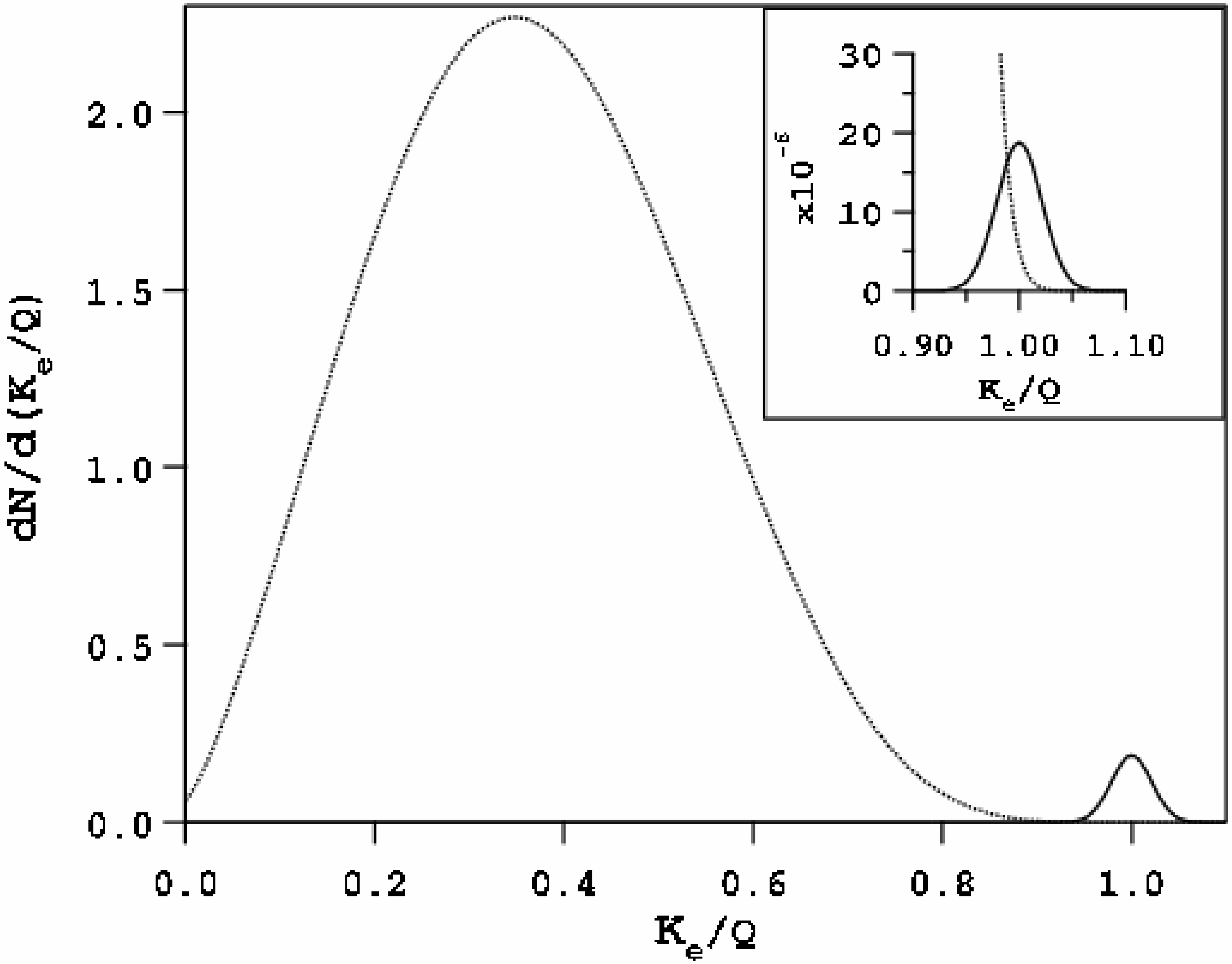


Table 1: Summary of experimentally measured $2\nu\beta\beta$ half-lives and matrix elements (^{136}Xe is an important exception where a limit is quoted).

Isotope	$T^{2\nu}_{1/2}$ (y)	References	$M^{2\nu}_{GT}$ (MeV^{-1})
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$	BAL96,BRU00	0.05
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$	KLA01a,AVI91,AAL96	0.15
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$	ELL92,ARN98	0.10
^{96}Zr†	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$	ARN99,KAW93,Wieser01	0.12
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$	DAS95,EJI91a,EJI91c, DES97,ALS97,ASH01	0.22
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	ARN96,DAN00,EJI95	0.12
^{128}Te$^{(1)}$	$(7.2 \pm 0.3) \times 10^{24}$	BER93,CRU93	0.025
^{130}Te$^{(2)}$	$(2.7 \pm 0.1) \times 10^{21}$	BER93	0.017
^{136}Xe	$> 8.1 \times 10^{20}$ (90% CL)	GAV00	<0.03
^{150}Nd†	$7.0^{+11.8}_{-0.3} \times 10^{18}$	DES97,ART95	0.07
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$	TUR91	0.05

(1) deduced from the geochemically determined half-life ratio ^{128}Te/^{130}Te

(2) geochemical result includes all decay modes; other geochemical determinations only marginally agree

(3) radiochemical result, again for all decay modes

$$M^{2\nu}_{GT} = \Sigma_m \frac{\langle f|\vec{\sigma}\tau^{+}|m\rangle \cdot \langle m|\vec{\sigma}\tau^{+}|i\rangle}{E_m - (M_i + M_f)/2}$$

The $2\nu\beta\beta$ matrix element consists of two amplitudes:
$<m||\sigma\tau^+||i>$ corresponds to the β^- strength of initial nucleus
$<f||\sigma\tau^+||m>$ corresponds to the β^+ strength of final nucleus
E_m is the energy of the intermediate 1^+ state

Note that the sum converges faster than expected, often already the first 1^+ state gives a dominant contribution.

The β^- and β^+ strengths are constrained by the Ikeda sum rule
$S(\beta^-) - S(\beta^+) = 3(N-Z)$

Note that for the $2\nu\beta\beta$ we need also <u>signs</u>, not just magnitudes of the GT matrix elements.

Various processes could contribute to the 0ν decay amplitude:

(light Majorana neutrinos, heavy neutrinos, right-handed current interactions, various SUSY particles, etc.) All of them imply “Physics beyond the Standard Model”.

Since we know that light neutrinos exist,

we primarily consider the process mediated by them.

If heavy virtual particles are exchanged,

short range physics issues are involved,

for the treatment in EFT see Prezeau, Ramsey-Musolf and P.V., Phys.Rev.D68,035501(2003)

For relation to the Lepton Flavor Violation processes

see Cirigliano, Kurylov, Ramsey-Musolf and P.V.

hep-ph/0406199

In $0\nu\beta\beta$ decay with the exchange of light Majorana neutrinos,

$$<m_{\beta\beta}> = \Sigma_i |U_{ei}|^2 m_i e^{i\alpha(i)},$$

where α(i) are the CP phases of U_{ei}.

These phases are relevant only for Majorana neutrinos; they do not affect flavor oscillations.

Independently of these phases

$$\mathrm{Max}[2|U_{ei}|^2 m_i] - \Sigma|U_{ei}|^2 \leqslant <m_{\beta\beta}> \leqslant \Sigma|U_{ei}|^2 m_i \,.$$

These upper and lower limits depend only on the oscillation parameters and on one mass m_{min}.

What do we know?

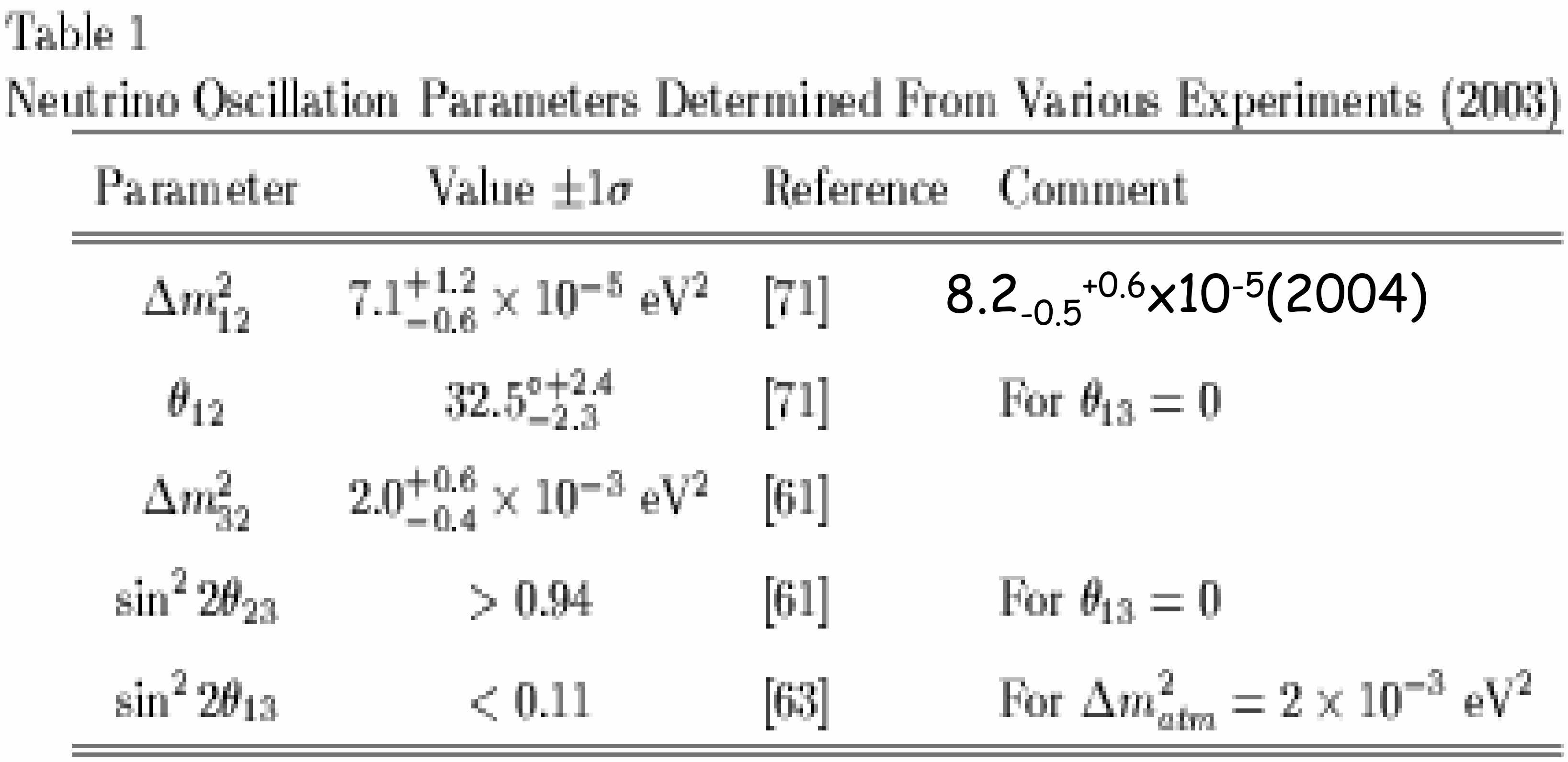
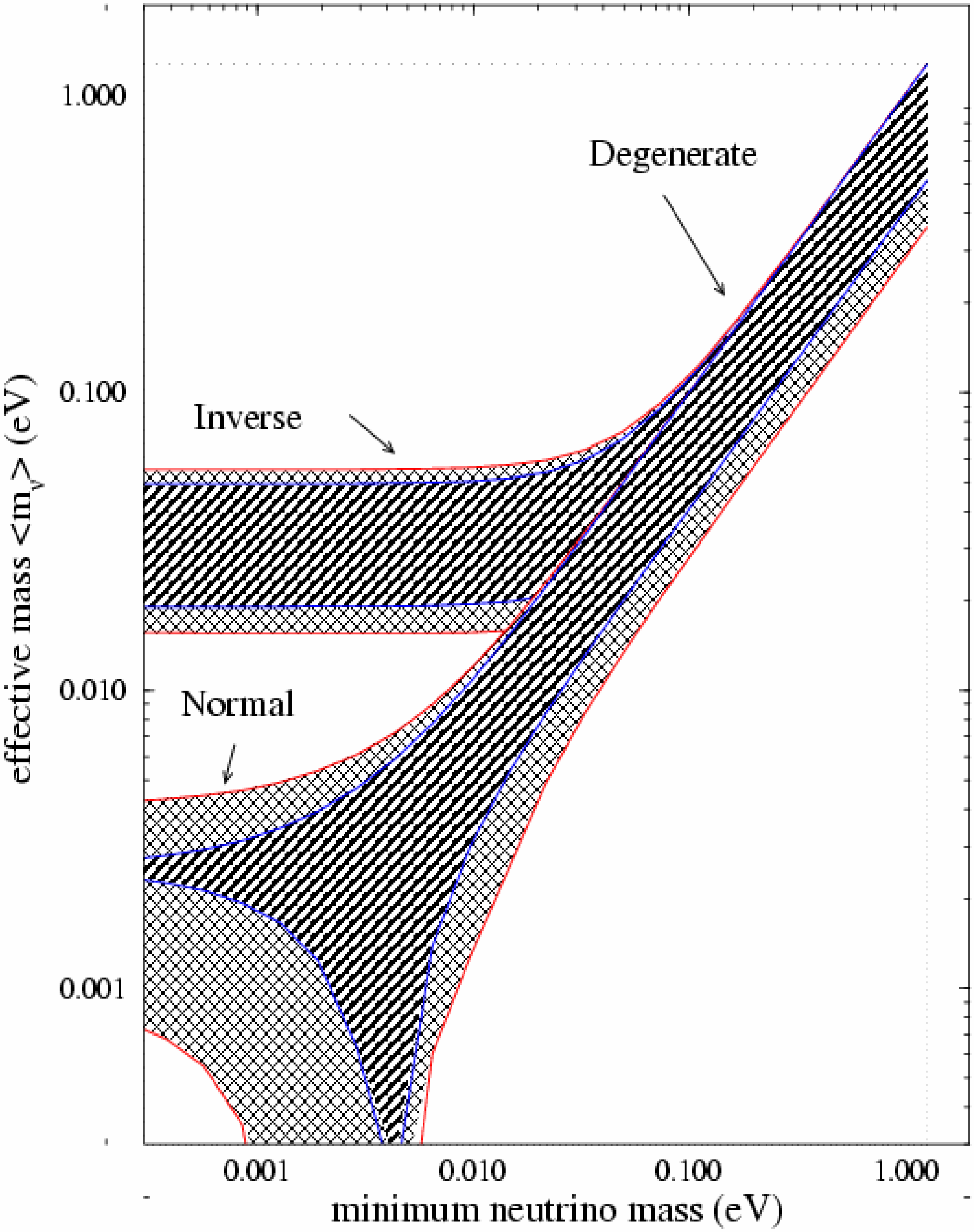


Table 1

Neutrino Oscillation Parameters Determined From Various Experiments (2003)

Parameter	Value ±1σ	Reference	Comment
Δm^2_{12}	$7.1^{+1.2}_{-0.6} \times 10^{-5}\ \mathrm{eV}^2$	[71]	$8.2_{-0.5}^{+0.6} x 10^{-5}$ (2004)
θ_{12}	$32.5^{\circ}{}^{+2.4}_{-2.3}$	[71]	For $\theta_{13} = 0$
Δm^2_{32}	$2.0^{+0.6}_{-0.4} \times 10^{-3}\ \mathrm{eV}^2$	[61]	
$\sin^2 2\theta_{23}$	> 0.94	[61]	For $\theta_{13} = 0$
$\sin^2 2\theta_{13}$	< 0.11	[63]	For $\Delta m^2_{atm} = 2 \times 10^{-3}\ \mathrm{eV}^2$

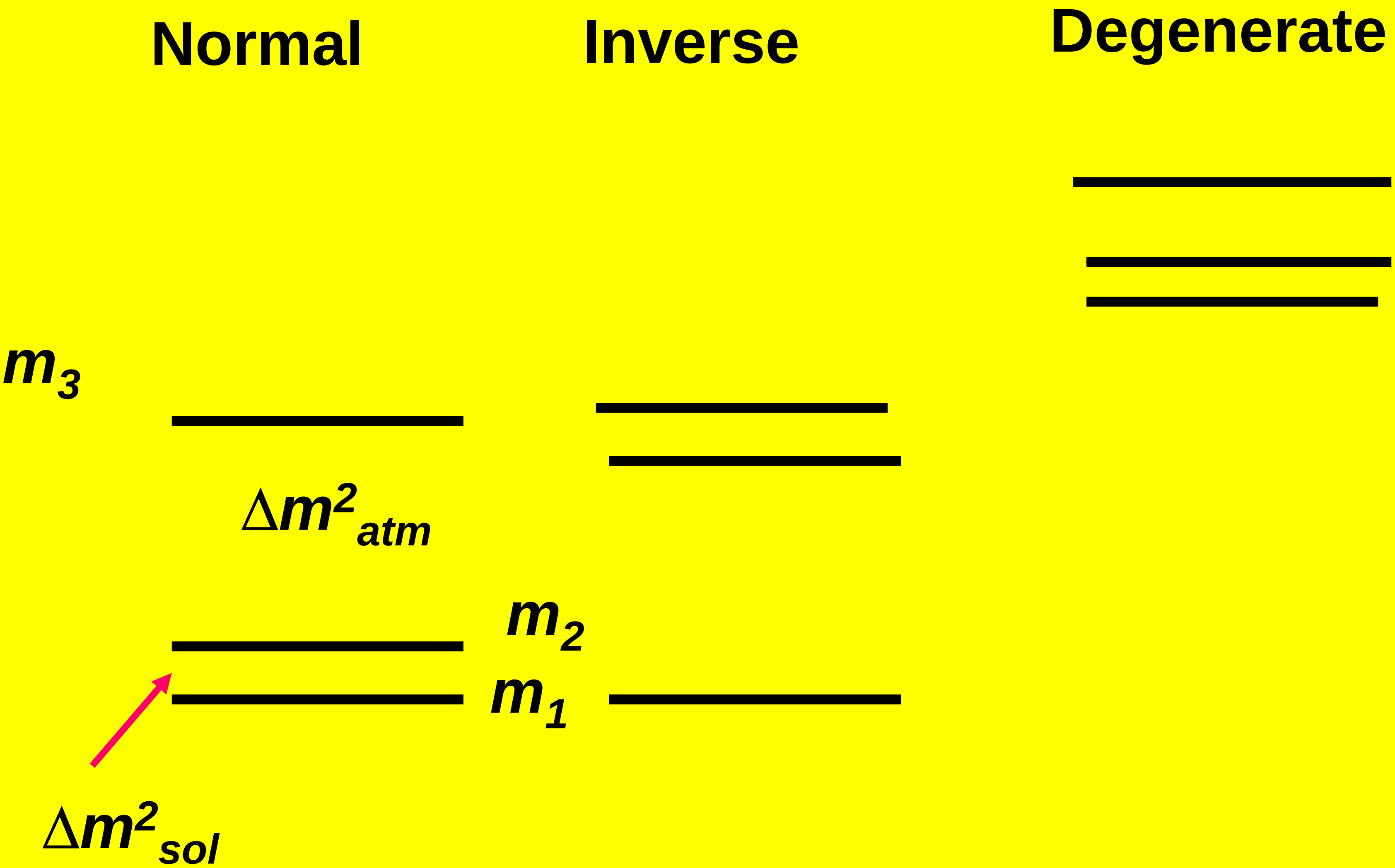


This is based on the parameters of the LMA solution.

The cross-hatched region is for 1σ errors.

Arrows indicate that by determining $<m_{\beta\beta}>$, even crudely we can fix the neutrino mass pattern.

Possible neutrino mass patterns



Normal

Inverse

Degenerate

m_3

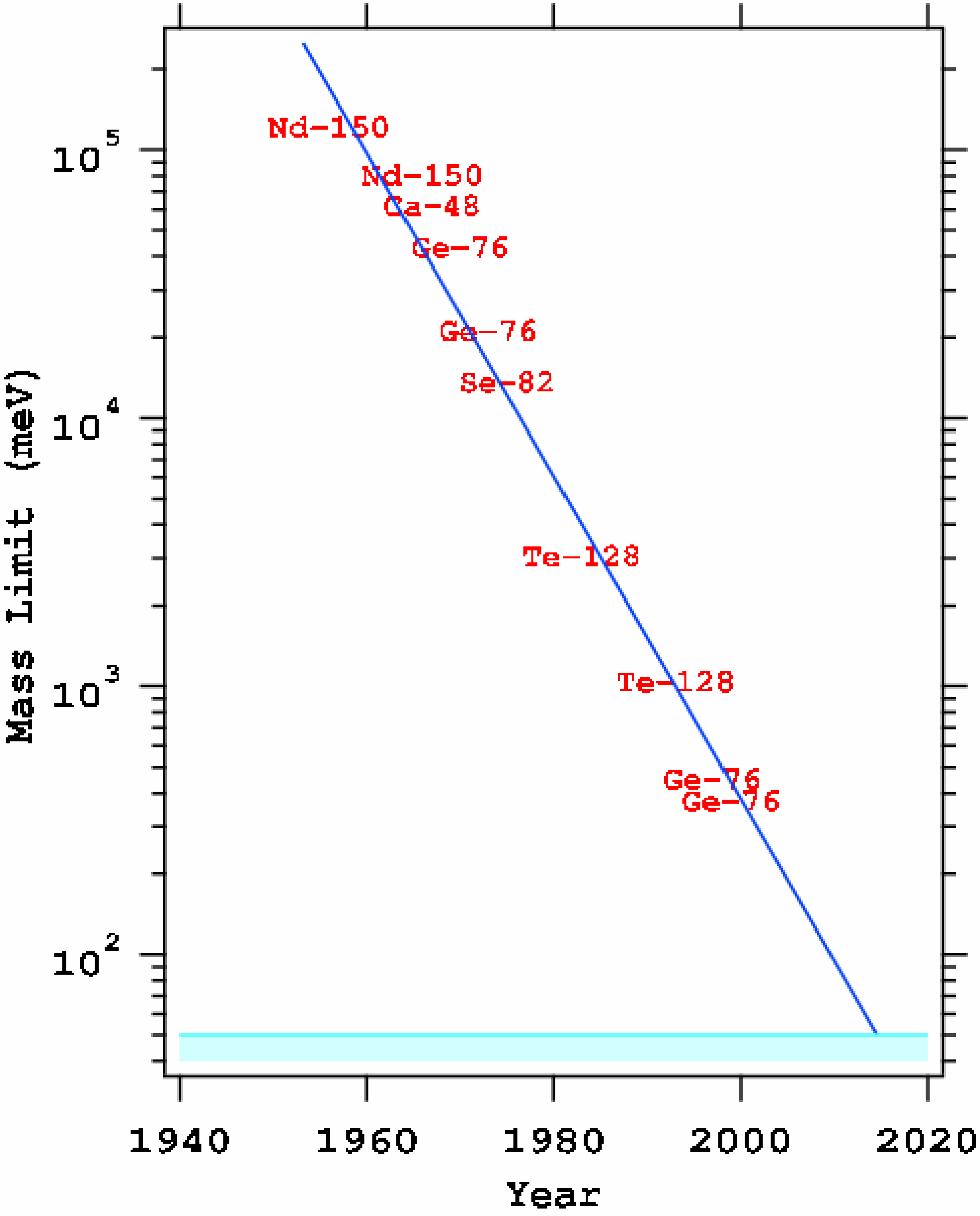
Δm^2_{atm}

m_2

m_1

Δm^2_{sol}

FIG. 4. Moore's plot for the $0\nu\beta\beta$ decay. The shaded blue region at bottom indicates the desired sensitivity range.



The decay rate is related to $\langle m_{\beta\beta} \rangle$ by

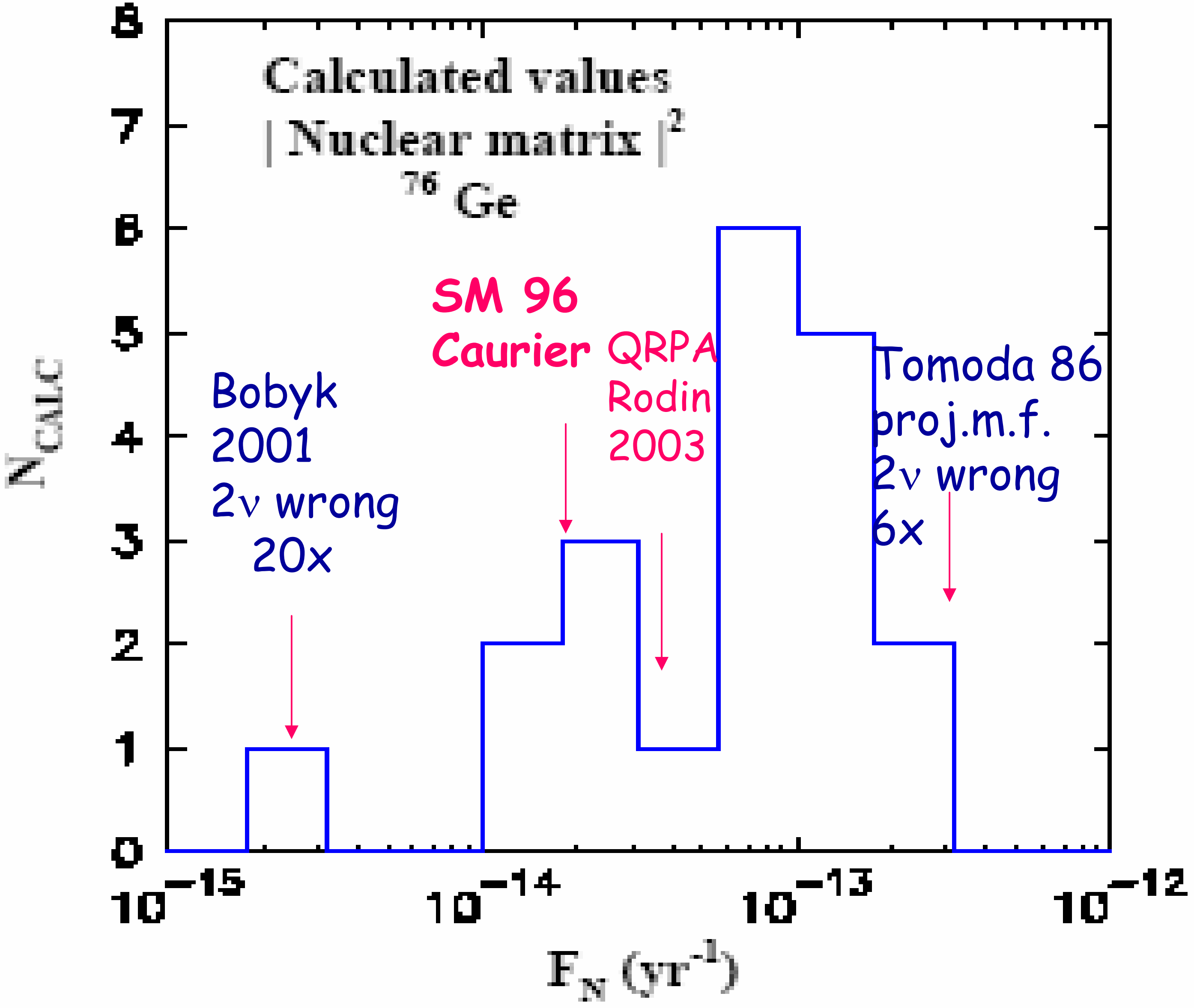
$1/T_{1/2} = G^{0\nu}(E_0,Z)\ |M|^2 \langle m_{\beta\beta} \rangle^2$,

Where $G^{0\nu}(E_0,Z)$ is calculable phase space factor,
and $|M|^2$ is the square of the nuclear matrix element,
calculable with difficulties.

The two basic and complementary methods of evaluating M are the nuclear shell model (SM) and the Quasiparticle Random Phase Approximation (QRPA) and its various modifications.

One often uses $C_{mm} = G^{0\nu}(E_0,Z)\ |M|^2\ m_e^2$ to characterize the matrix elements

Histogram from Bahcall et al. hep-ph/0403167



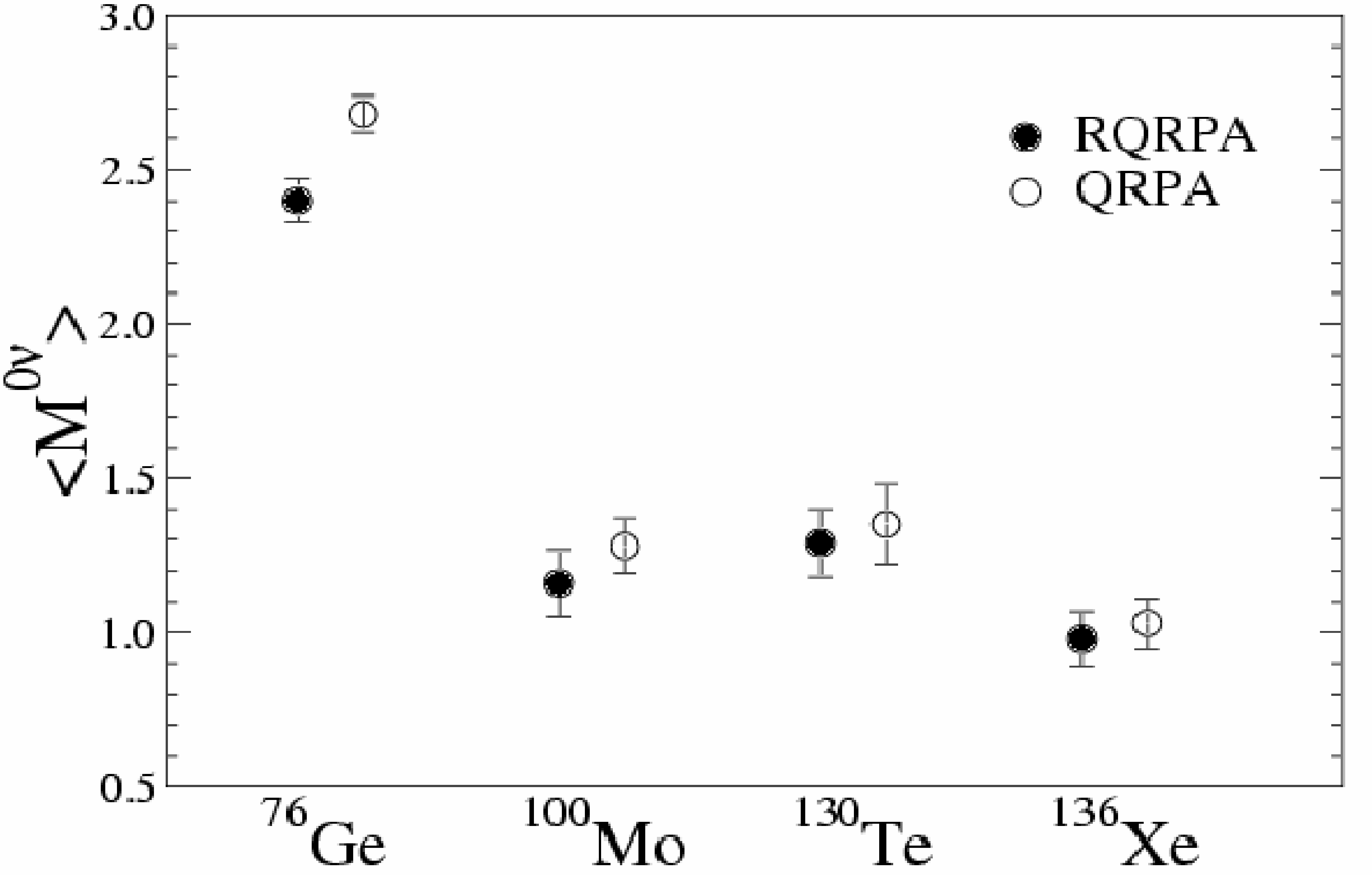
Bobyk
2001
2ν wrong
20x

SM 96
Caurier

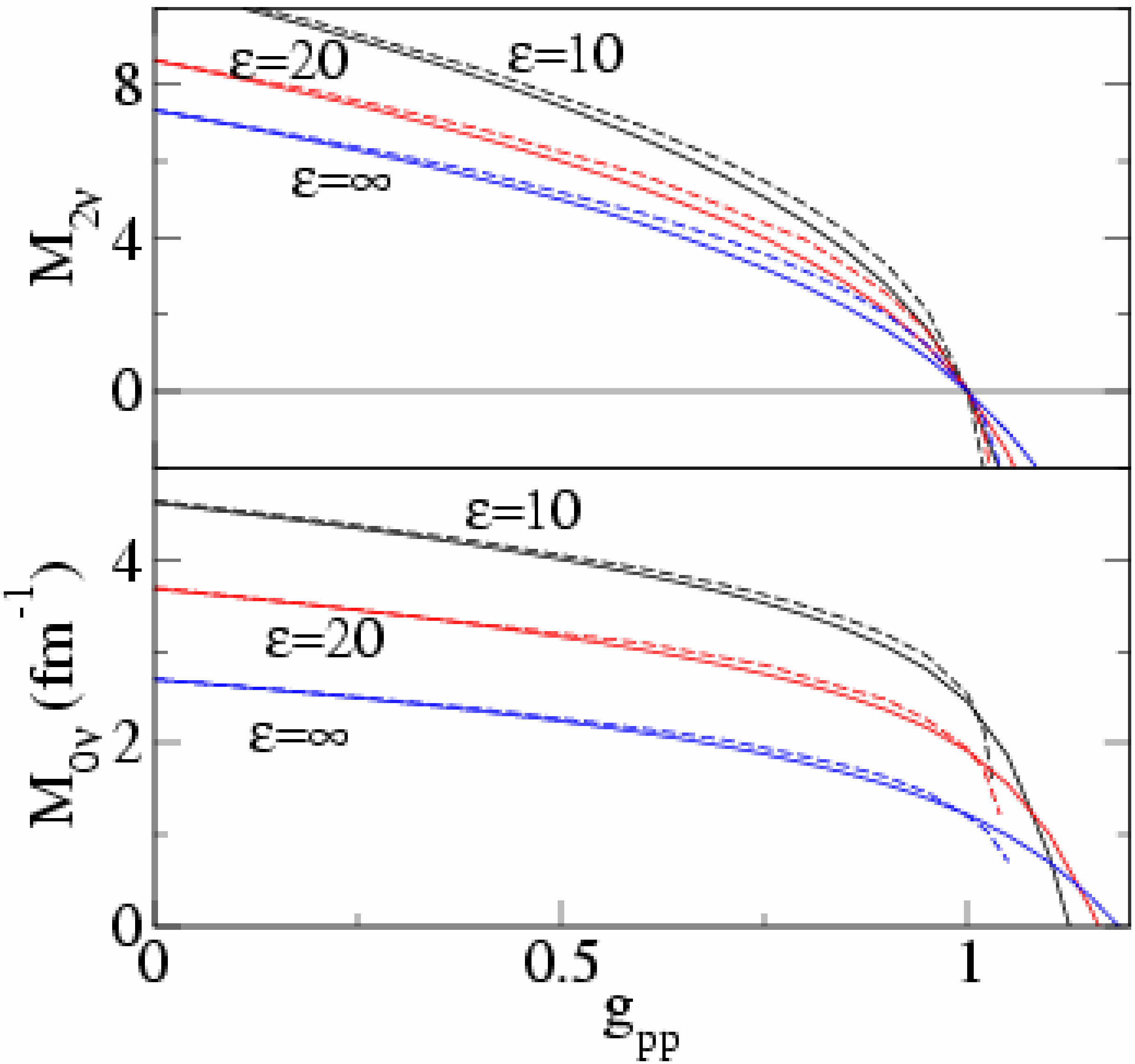
QRPA
Rodin
2003

Tomoda 86
proj.m.f.
2ν wrong
6x

Average matrix elements and their variance see Rodin et al. Phys.Rev. C68,044302(2003)



From Engel & Vogel, PRC69,034304(2004)
Comparison of exact (full) and QRPA (dashed) m.e.



Two shells, ε apart, schematic force, but similar to the treatment of real nuclei.

Comparison of the shell model and RQRPA matrix elements:

Shell model: Caurier et al., PRL 77(1996)1954 and
Caurier et al., Nucl. Phys. A654(1999)973c

QRPA: Rodin et al., Phys. Rev. C68(2003)044302 and
private comm. (for ^{82}Se)

Nucleus	C_{mm}(s.m.)	C_{mm}(RQRPA) (in 10^{-14} y^{-1})
^{76}Ge	1.9	3.6
^{82}Se	10.9	11.3
^{130}Te	4.5	7.4
^{136}Xe	2.2	3.4

Note: $1/T_{1/2} = C_{mm} * (m_\nu/m_e)^2$

Conclusions

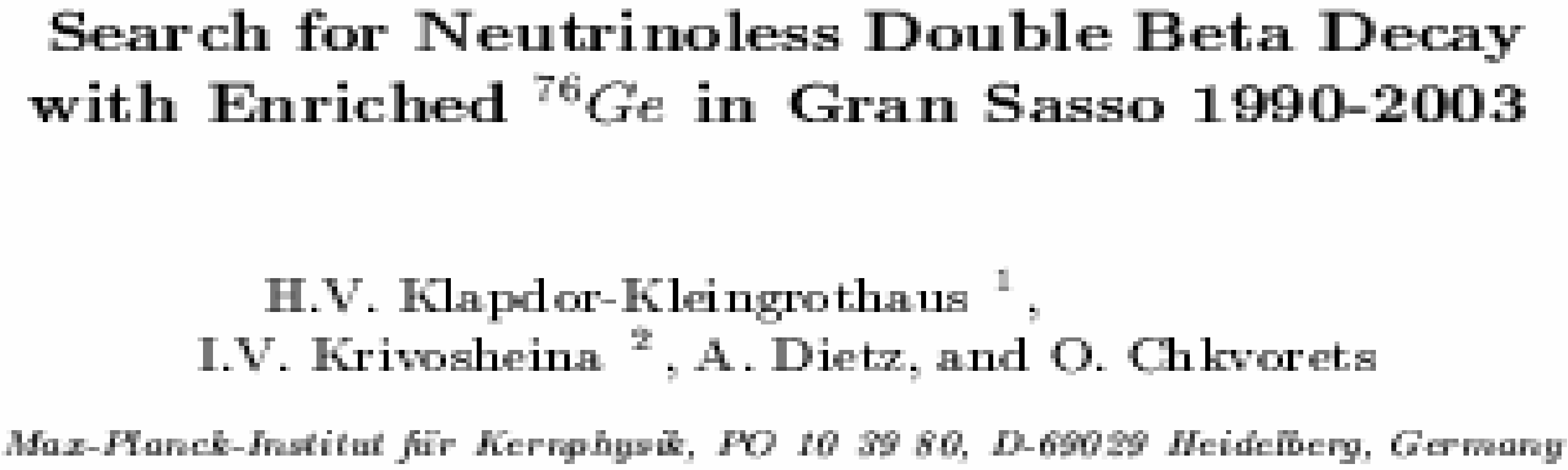
- **There is a good possibility that $0\nu\beta\beta$ decay corresponding to $<m_{\beta\beta}> \sim 10\ meV$ really exists.**
- **It is of extreme interest to observe it.**
- **This can be achieved only with more challenging and costly experiments than those currently running.**
- **There is a wealth of proposals; the best of them clearly deserve support.**
- **Hand in hand with the development of novel detection schemes, the community should also concentrate on attempts to improve the evaluation of the nuclear matrix elements,**

APS Joint Study on the Future of Neutrino Physics (2004)

(preliminary version, subject to change):

Will recommend that a program of sensitive searches for neutrinoless double beta decay be initiated as soon as possible. Most likely a phased approach, with several scalable 100-200 kg experiments, will be recommended.

This is based on the understanding that the answer to the question whether neutrinos are their own antiparticles is a crucial ingredient in the development of a "New Standard Model"



Search for Neutrinoless Double Beta Decay with Enriched ^{76}Ge in Gran Sasso 1990-2003

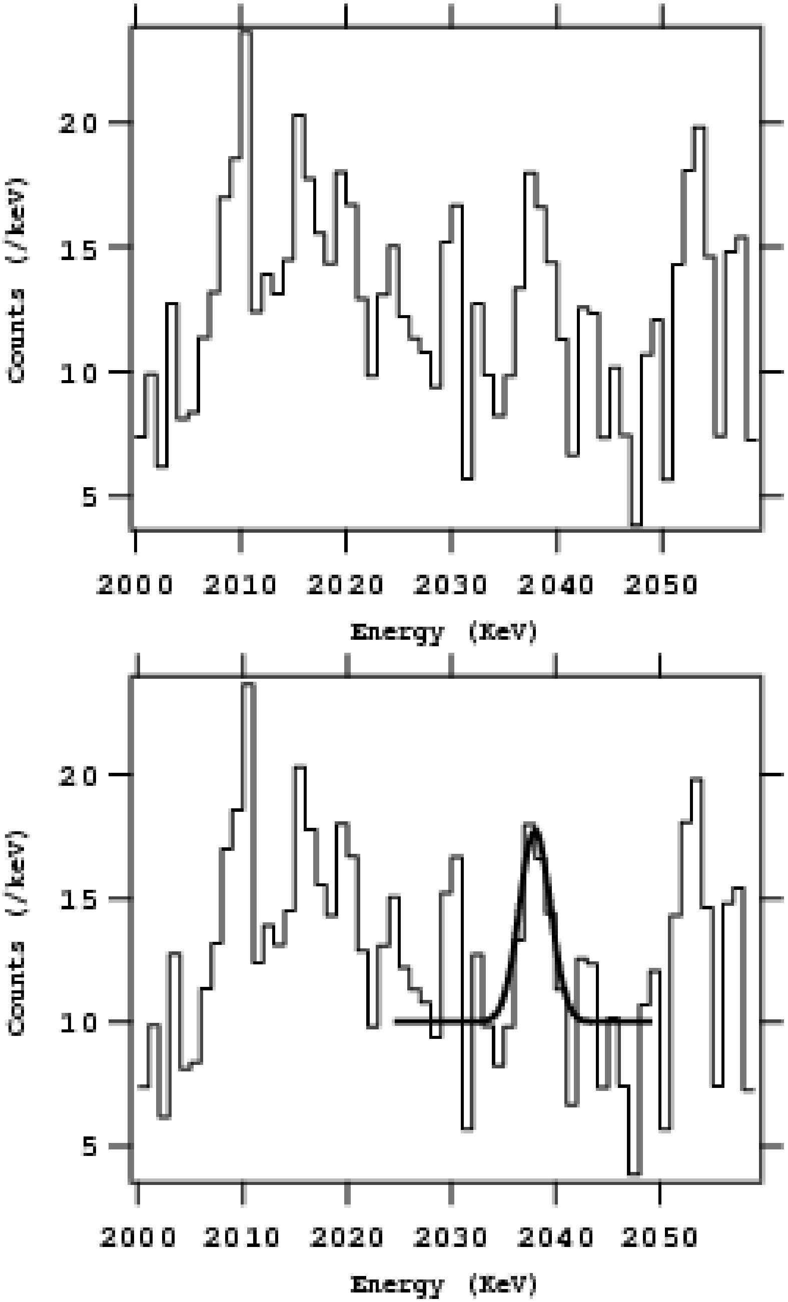
H.V. Klapdor-Kleingrothaus [1],
I.V. Krivosheina [2], A. Dietz, and O. Chkvorets

Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany

Phys. Lett. **B586**, 198 (2004); hep-ph/0404088

All detectors, 71.7 kg y, 28.75 ± 6.86 events at 2039 keV, the Q-value for $0\nu\beta\beta$ decay

This is interpreted as $T_{1/2} = 1.15_{-0.5}^{+2.99} \times 10^{25}$ y or $\langle m_{\beta\beta} \rangle = 0.44_{-0.2}^{+0.14}$ eV for the matrix elements chosen by the authors.



From Klapdor-Kleingrothaus, Dietz, Krivosheina, Chkvorets, hep-hp/0403018.
71.7 kg-y exposure, spectrum without and with the `$0\nu\beta\beta$' line.
Additional lines at 2010, 2017, 2022, 2053 are assigned to the ^{214}Bi decay, line at 2030, previously not seen, is of an unknown origin.
Unidentified previously fitted lines at ~2066 and 2075 keV are not shown now.

- To confirm or reject the KDHK claim of the $0\nu\beta\beta$ discovery convincingly one needs 5-10 kmole-years exposure with low background.
- This is in accord with plans of most groups. So, no change in strategy is required. It might take ~3-5 years to accomplish.
- One needs 100-200 kg of source material, and lower background than KDHK to be able to reject or confirm the claim at ~5σ.

Quote from the executive summary (preliminary version, subject to change) the APS Joint Study on the Future of Neutrino Physics (2004)

"We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless double beta decay be initiated as soon as possible."

It continues by noting that "An understanding of nature through a New Standard Model cannot be completed without the answer to this question"