Neutrinos and Neutrinoless Double Beta Decay*

(from a modern perspective)

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- * J.D. Vergados, H. Ejiri and F. Simkovic, Reports of Progress in Physics (in press)

Facts about neutrinos (after 70 years)

--We know for some time that:

- There exist three distinct families of left handed

neutrinos: $(\nu^0)_L = (\nu_e, \nu_\mu, \nu_\tau)_L$

- These neutrinos are distinct from the associated antineutrinos
- How these neutrinos interact

-- We have learned from neutrino oscillations that:

- the neutrinos are massive. We know the two mass squared differences.
- The neutrinos are admixed. We know the two mixing angles quite well and we have a good idea about the third.

Issues involving neutrinos (after 70 years)

--We do not know:

- The absolute scale of their mass
- The value of the CP violating phase.
- The nature of the mass eigenstates, i.e whether they are of Majorana type (particle=antiparticle) or Dirac type (particle #antiparticle)

Main needed experiments for ν's

- To determine the absolute mass scale:

--Decay experiments: Sensitivity 0.1 eV (KATRIN)

--Astrophysical and cosmological observations: Sensitivity sub eV

--Neutrinoless (0ν) ββ- decay : Sensitivity meV

- To determine the CP violating phase : Neutrino oscillations involving both neutrinos and antineutrinos
- To settle the controversy of Dirac vs Majorana : Neutrinoless double beta decay

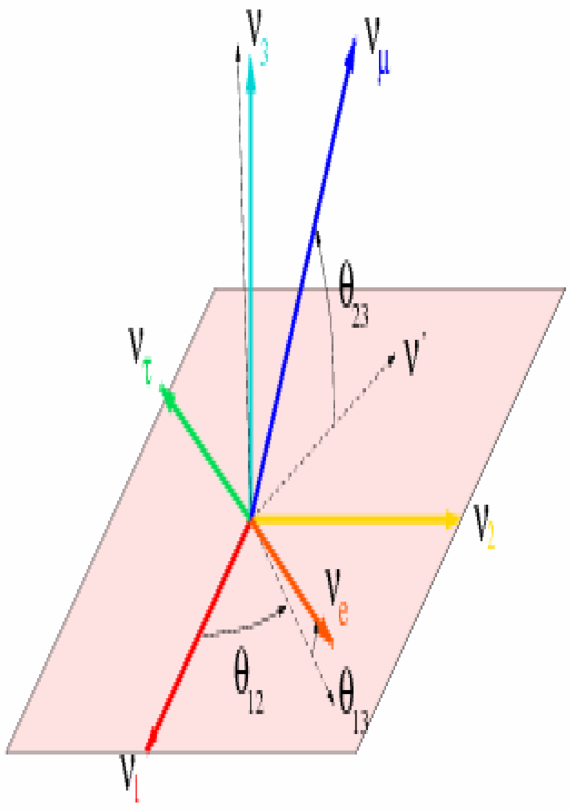
Experiments: Use Neutrino as probes

- Since the interactions of neutrinos are well known and weak we can use neutrinos as probes to study other systems:
- The interior of stars (even our Sun, this way)
- The interior of the Earth (geoneutrinos)
- Detect supernovae and study the process of collapsing stars
- Very distant objects, otherwise obscured, e.g. EM probes maybe distorted on the way

Neutrino features

- Two types of neutrinos
- i) Those produced in weak interactions
  $(\nu^0)_L = (\nu_e, \nu_\mu, \nu_\tau)_L$
- ii) the eigenstates of the world Hamiltonian
  $\nu_L = (\nu_1, \nu_2, \nu_3)_L$ with masses (m_1, m_2, m_3) respectively.
- There exists a unitary transformation U (mixing matrix) connecting the two:
  $(\nu^0)_L = U_{PMNS}$ (3x3 matrix) ν_L ---> $\nu_{eL} = \Sigma_j U_{ej} \nu_{jL}$

Parameterization of the Mixing Matrix $U=U_{PMNS}$ ($c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$)



$$U = R_{23} W_{13} R_{12}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\vartheta_{23} \simeq \vartheta_{\mathrm{ATM}}$ $\quad$ $\vartheta_{13} = \vartheta_{\mathrm{CHOOZ}}$ $\quad$ $\vartheta_{12} = \vartheta_{\mathrm{SUN}}$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

Neutrino Oscillations Can Determine

- The absolute value of the two possible mass^2 differences , e.g,

$\Delta m^2_{12}=|m^2_2 - m^2_1|= \Delta m^2_{SUN}$,
$\Delta m^2_{31}=|m^2_3 - m^2_1|= \Delta m^2_{ATM}$

- All three mixing angles θ_{ij}
- The CP violating phase δ using both neutrinos and antineutrinos
- The signs of Δm^2_{ij} (in principle)

Table I: Best fit values from ν oscillation data (solar, atmospheric, reactor (KamLAND and CHOOZE) and K2K experiments)

Schwetz&Tortola & Valle arXiv: 0808.2016(hep-ph) (also Pascoli & Petcov arXiv0711.4993 (hep-ph)

Parameter	value	reference
Δm^2_{ATM}	$(2.43 \pm 0.13)10^{-3}\text{eV}^2$	MINOS
Δm^2_{SUN}	$(7.65^{+0.13}_{-0.20})10^{-5}\text{eV}^2$	Global Fit
$\sin\theta^2_{23}$	$0.50^{+0.07}_{-0.06}$	MINOS
$\tan\theta^2_{12}$	$0.452^{+0.035}_{-0.033}$	KamLAND
$\sin 2\theta^2_{13}$	0.092 ± 0.016 (stat)± 0.005 at $5.2\ \sigma$ (syst)	Daya Bay
$\sin 2\theta^2_{13}$	0.085 ± 0.029 (stat)± 0.042 (syst) (68% CL)	Double CHOOZ
$\sin 2\theta^2_{13}$	0.103 ± 0.013 (stat) ± 0.011 (syst)	RENO
$\sin 2\theta^2_{13}$	$0.04 < \sin 2\theta^2_{13} < 0.34$	T2K

Issues not settled by Neutrino Oscillations:

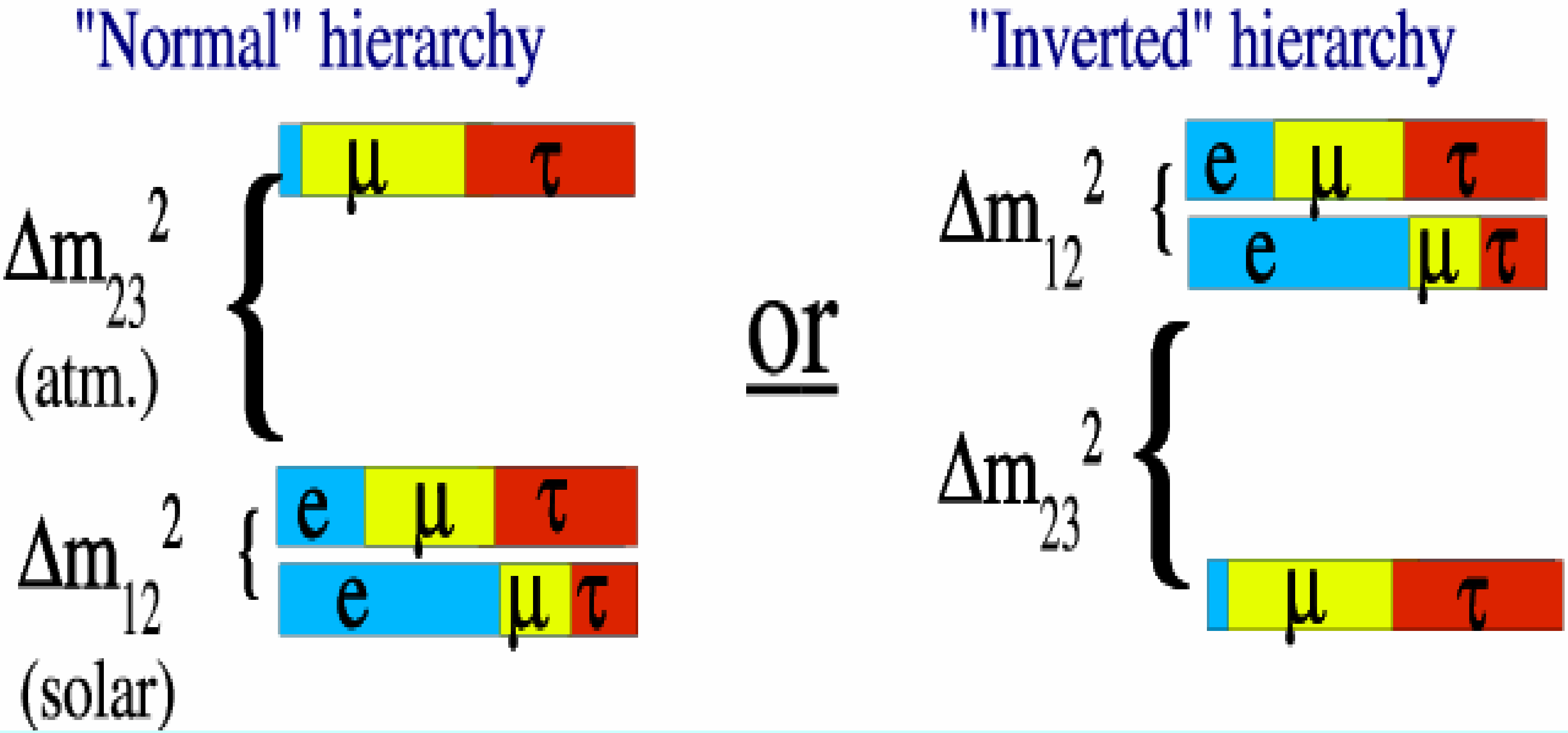
- Whether the neutrinos are Majorana or Dirac particles
- The scale of neutrino masses
- (Not yet) the sign of

$$\Delta m^2 = m^2_3 - m^2_2 \text{ or } \Delta m^2 = m^2_3 - m^2_1 \text{ , } (m_2 > m_1)$$

Thus the following scenarios emerge:

- Normal hierarchy: $\Delta m^2 > 0$ or $m^2_3 > m^2_2$
- Inverted hierarchy: $\Delta m^2 < 0$ or $m^2_3 < m^2_1$
- The Degenerate : $\Delta m^2 << m^2_i$, $i=1,2,3$

The Mass Hierarchies
- Flavor Content



I: Neutrino mass scale in β decay

Mass in the two scenarios

- Normal Spectrum (NS), $m_1 < m_2 < m_3$:

$$\Delta m^2_{SUN} = m_2^2 - m_1^2\,,\ \Delta m^2_{ATM} = m_3^2 - m_1^2$$

$$m_0 = m_1,\ m_2 = \sqrt{\Delta m^2_{SUN} + m_0^2}\,,\ m_3 = \sqrt{\Delta m^2_{ATM} + m_0^2}$$

- Inverted Spectrum (IS), $m_3 < m_1 < m_2$:

$$\Delta m^2_{SUN} = m_2^2 - m_1^2\,,\ \Delta m^2_{ATM} = m_2^2 - m_3^2$$

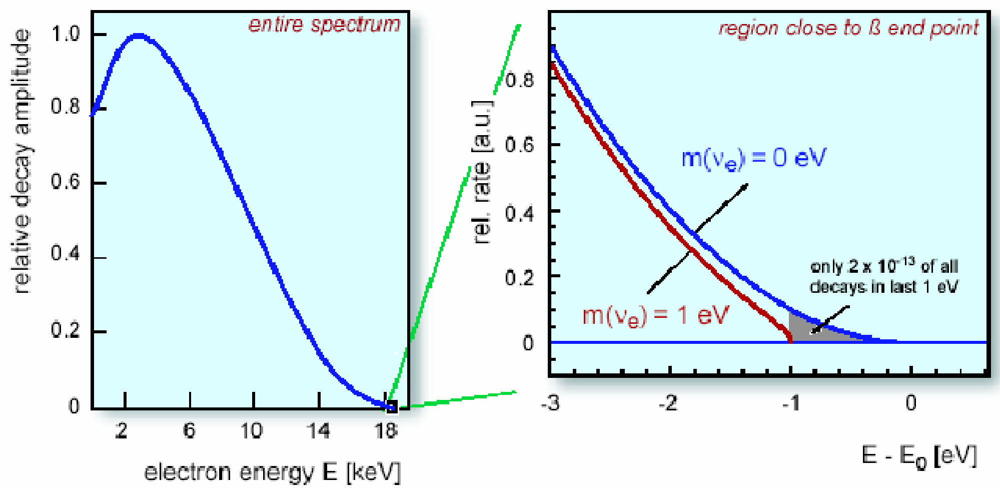
$$m_0 = m_3,\ m_2 = \sqrt{\Delta m^2_{ATM} + m_0^2},$$

$$m_1 = \sqrt{\Delta m^2_{ATM} - \Delta m^2_{SUN} + m_0^2}$$

Spectrum of triton beta decay

β-decay endpoint measurement

Essentially a search for a distortion in the shape of the b-spectrum in the endpoint energy region



$$dN(E) = K|M|^2F(Z,R,E)\ p_eE\ (E_0-E)\ \{(E_0-E)^2-m^2_{\nu_e}c^4\}^{1/2}\ dE$$

β-καταστροφή τριτίου: $<m_\nu> \leq 2.3$eV

Mass in the two scenarios

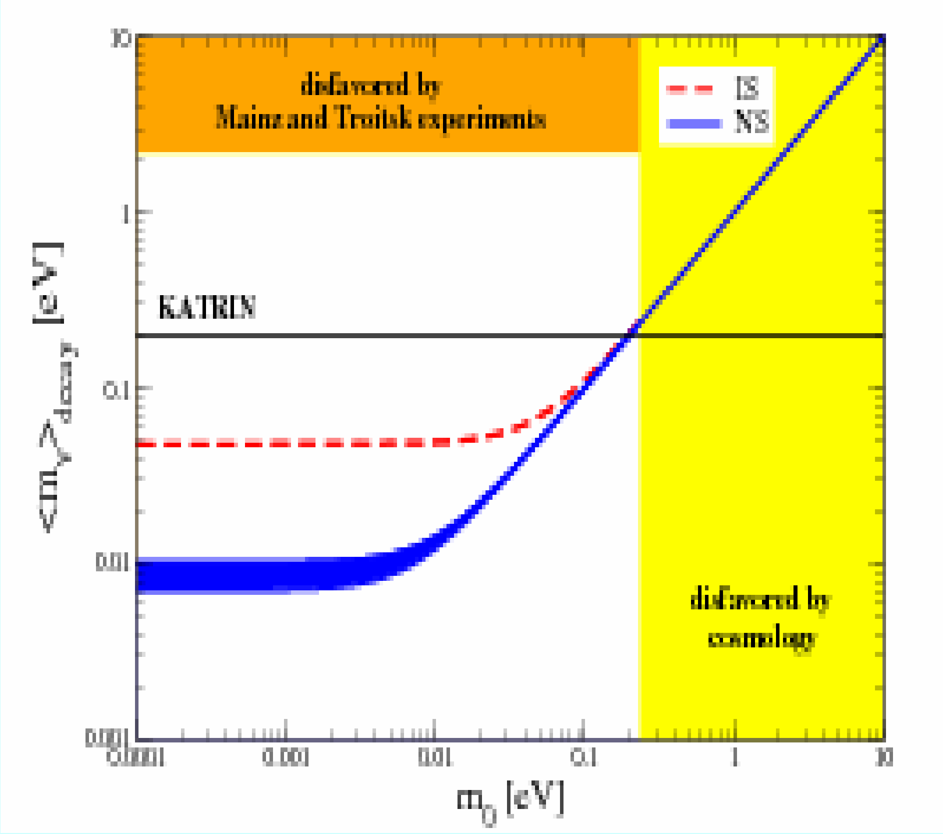
N-H (N-S, upper) &

I-H (N-S) lower)

$$< m_\nu >_{\rm decay} = \sqrt{c_{12}^2 c_{13}^2 m_1^2 + s_{12}^2 c_{13}^2 \left(\Delta m^2_{\rm SUN} + m_1^2\right) + s_{13}^2\left(\Delta m^2_{\rm ATM} + m_1^2\right.}$$

$$< m_\nu >_{\rm decay} = \left(s_{13}^2 m_3^2 + s_{12}^2 c_{13}^2\left(\Delta m^2_{\rm ATM} + m_3^2\right) + c_{12}^2 c_{13}^2\left(\Delta m^2_{\rm ATM} - \Delta m^2_{\rm SUN} + m_3^2\right)\right)^{1/2}$$

Measured mass as a function of m_0



II:Cosmological bound (CMB, etc): $m_\nu \le 0.71$
Photometric red shift survey: $m_\nu \le 0.28$ eV

Mass in the two scenarios

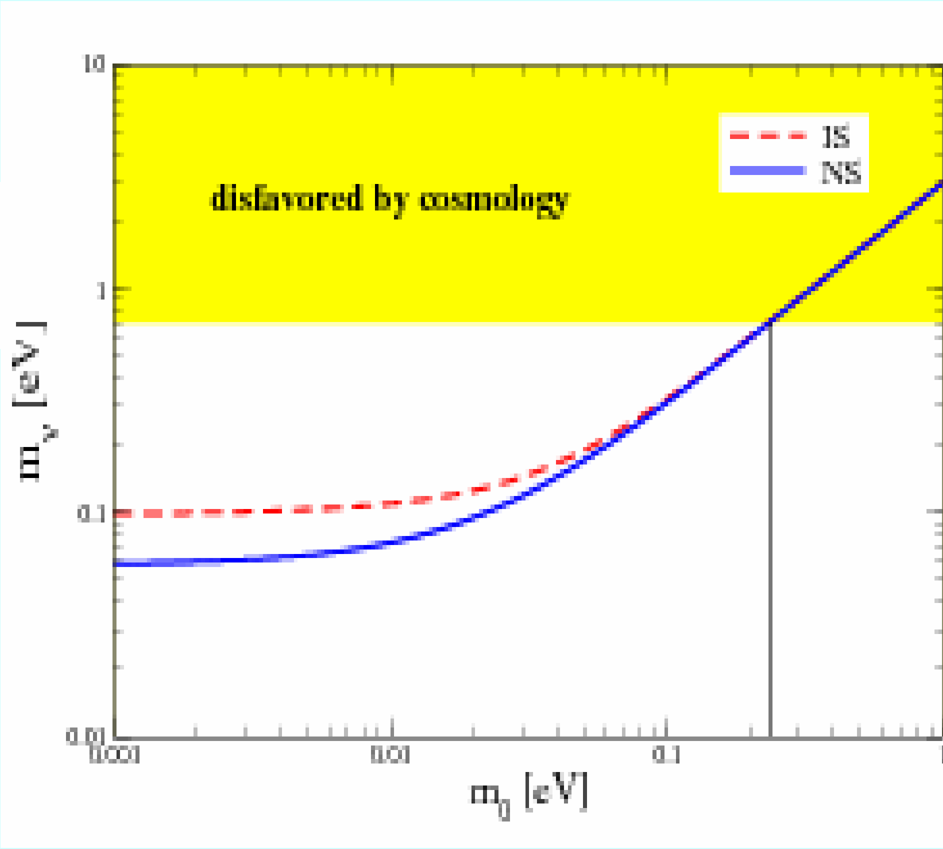
N-H (N-S, upper) &

I-H (N-S), lower)

Extracted mass as a function of m_0

$$m_\nu = m_1 + \sqrt{\Delta m^2_{SUN} + m_1^2} + \sqrt{(\Delta m^2_{ATM} + m_1^2)}$$

$$m_\nu = m_3 + \sqrt{(\Delta m^2_{ATM} + m_3^2)} + \sqrt{(\Delta m^2_{ATM} - \Delta m^2_{SUN} + m_3^2)}$$

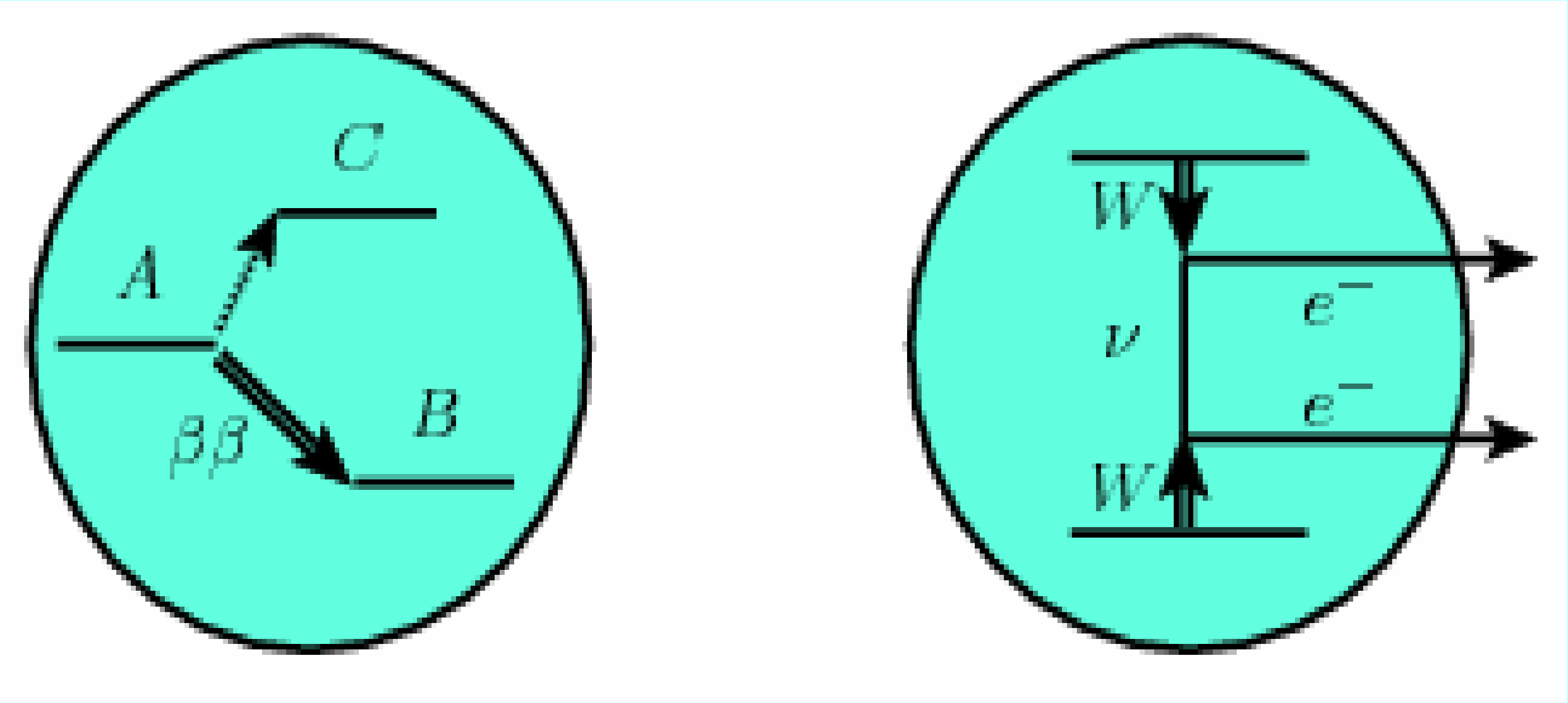


III: Neutrino mass in double beta decay:

Ordinary Beta Decay of A(N,Z) is Forbidden

Double Beta Decay of A(N,Z) is allowed

a fempto (10^{-15} m) laboratory!



Searching for an Old Lepton Violating Process:

About 20 nuclei are stable against beta decay

But not against double beta decay

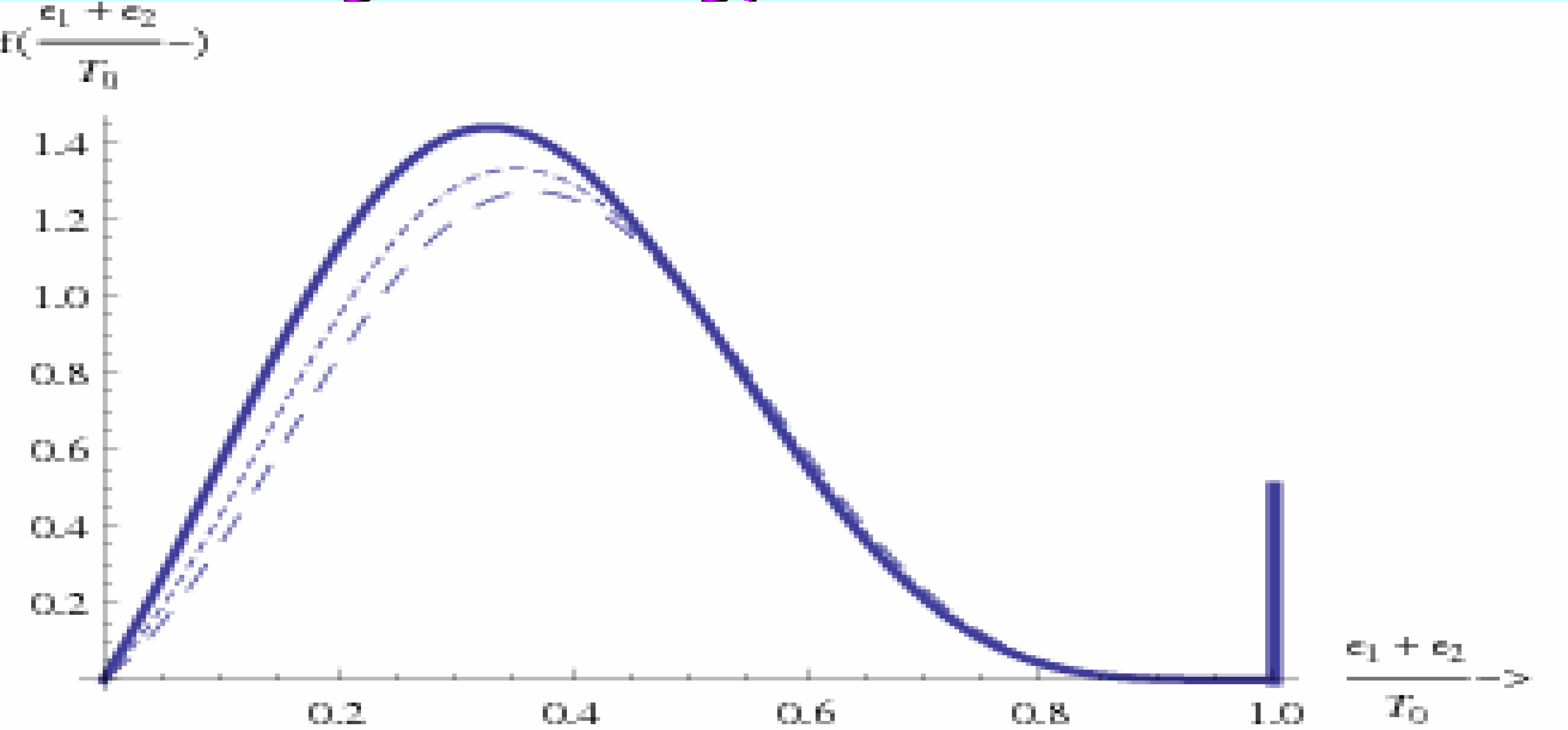
- $N(A,Z) \rightarrow N(A,Z+2) + e^- + e^- + 2$ anti-ν_e's (2ν $\beta\beta$-decay); (non exotic, observed in many systems)
- $N(A,Z) \rightarrow N(A,Z+2) + e^- + e^-$ (0ν $\beta\beta$-decay) Q
- $N(A,Z) \rightarrow N(A,Z-2) + e^+ + e^+$ $Q-4m_e c^2$

  (double positron emission)
- $e^-_b + N(A,Z) \rightarrow N(A,Z-2) + e^+$ $Q-2m_e c^2$

  (electron positron conversion)
- $e^-_b + e^-_b + N(A,Z) \rightarrow N(A,Z-2) + 2$ X-rays Q

  (Double electron capture Vergados (1982); Sujkowski and S. Wycech 2004 Simkovic et al 2009, many groups 2011)

Measure the sum of the energies of the two electrons. 0ν $\beta\beta$ is a discreet line at the end point. 2ν $\beta\beta$ has a continuous spectrum. A need for good energy resolution.



Main issues in 0ν ββ- decay

- The possible mechanisms : Particle Physics Issues

--The neutrino mass mechanism

--Other mechanisms contributing to 0ν ββ- decay and affecting the neutrino mass extraction

- Nuclear Physics issues:

--The effective transition operator associated with each mechanism

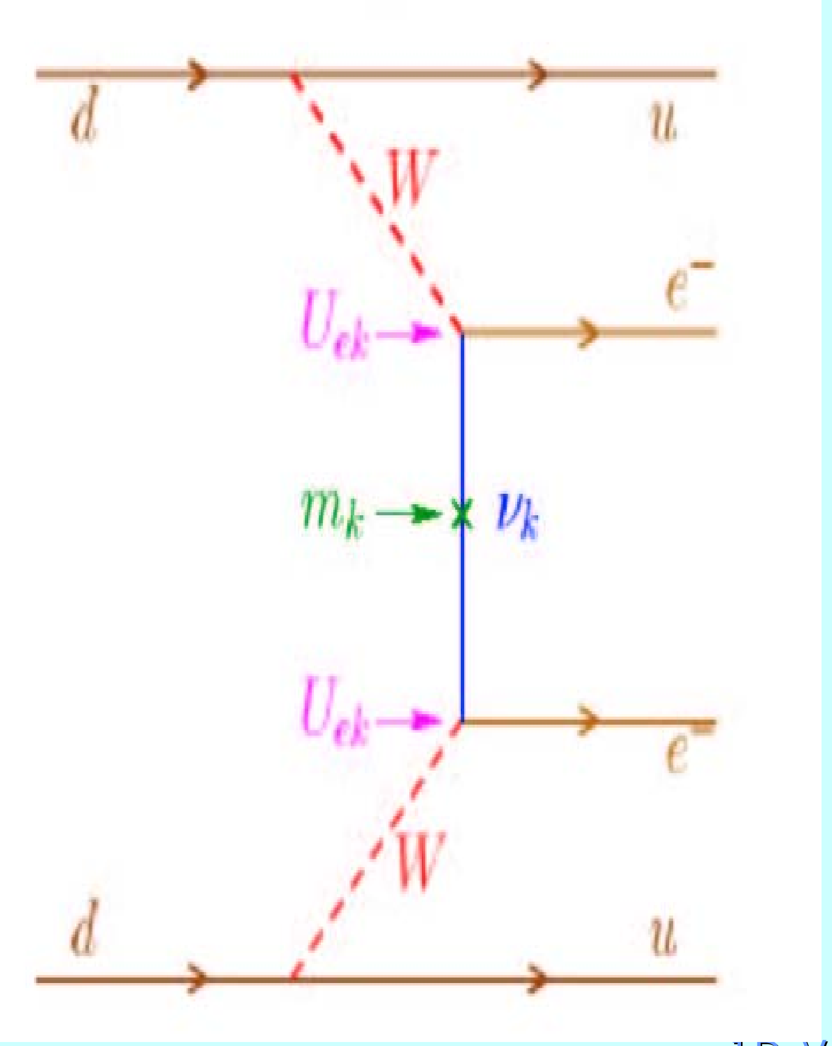
--Methods of Calculating the Nuclear ME

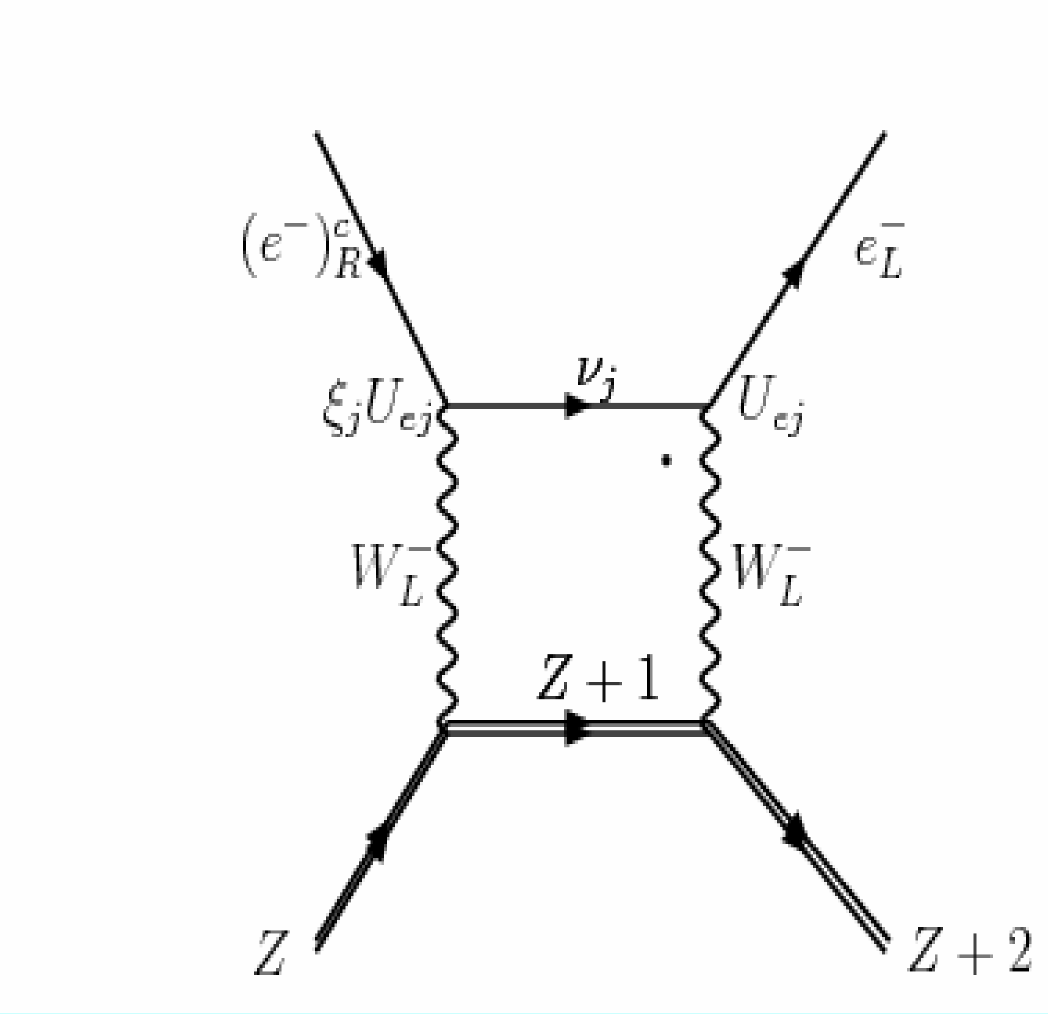
- How can these mechanisms be disentangled to reliably extract the scale of neutrino mass?

Diagrammatic Representation of 0ν-ββ decay

(Light neutrino:Amplitude proportional to neutrino mass)

Quark Level **Nuclear Level**





lower neutrino mass bound from 0ν ββ-decay: $|<m_\nu>|$ (JDV, Ejiri,Simkovic, arXiv:1205.0649)

Mass in the two scenarios

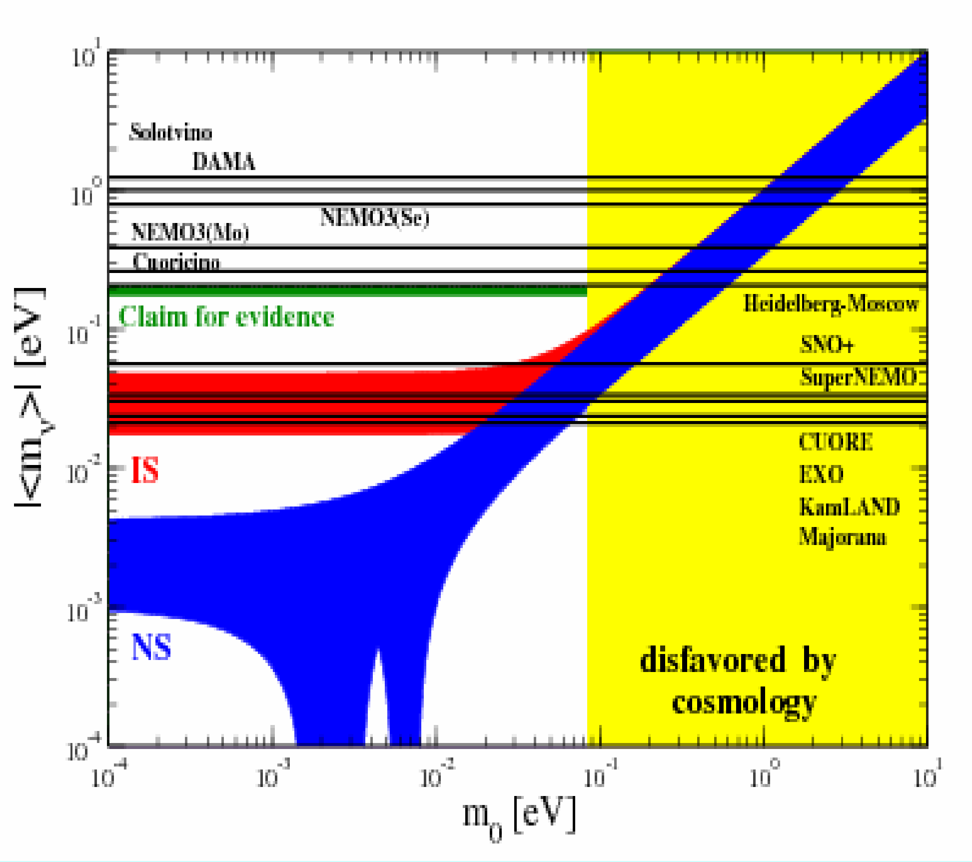
N-H (N-S, upper) &

I-H (I-S) lower)

$$< m_\nu > = c_{12}^2 c_{13}^2 m_1 e^{2i\alpha_1} + s_{12}^2 c_{13}^2 e^{2i\alpha_2}\sqrt{\Delta m^2_{\mathrm{SUN}} + m_1^2} + s_{13}^2\sqrt{(\Delta m^2_{\mathrm{ATM}} + m_1^2)},$$

$$< m_\nu > = s_{13}^2 m_3 + s_{12}^2 c_{13}^2 e^{2i\alpha_2}\sqrt{(\Delta m^2_{\mathrm{ATM}} + m_3^2)} + c_{12}^2 c_{13}^2 e^{2i\alpha_1}\sqrt{(\Delta m^2_{\mathrm{ATM}} - \Delta m^2_{\mathrm{SUN}} + m_3^2)}.$$

Extracted mass as a function of m_0



0ν Double Beta decay lifetime

For light neutrino nuclear and particle physics separate!

$$(T^{0\nu}_{1/2})^{-1} = G_{01}(A,\epsilon_0)|M^{0\nu\beta\beta}|^2|\eta_\nu|^2 \quad , \quad \eta_\nu = \frac{< m_\nu >}{m_e}$$

A Measurement of Lifetime involves the detection of the two produced electrons

It is a Very hard task

- Very Low counting rate
- Terrible Backgrounds

1. $M^{0\nu\beta\beta}$ Is the nuclear ME . It should be as large as possible. It is also very hard to calculate:

- The nuclei involved have complicated structure
- One encounters cancellations

2. G_{01}: Kinematical well known function. It should be as large as possible. Q as large as possible

3. η_ν: Fundamental Particle Physics

- To be extracted from the data ! Still elusive after 70 years

The nuclear ME for various models. Note the convergence of the values (J.D.V, Ejiri, Simkovic, arXiv:1205.0649)

Transition	$\|M^{0\nu}_{\nu}\|$					
	ISM [235, 293]	QRPA (TBC) [288, 184]	QRPA (J) [296, 297, 298]	IBM-2 [130]	PHFB [129]	EDF [131]
$^{48}Ca \rightarrow {}^{48}Ti$	0.61, 0.57					1.91
$^{76}Ge \rightarrow {}^{72}Se$	2.30	4.92	4.72	5.47		3.70
$^{82}Se \rightarrow {}^{82}Kr$	2.18	4.39	2.77	4.41		3.39
$^{96}Zr \rightarrow {}^{96}Mo$		1.22	2.45		2.78	4.54
$^{100}Mo \rightarrow {}^{100}Ru$		3.64	2.91	3.73	6.55	4.08
$^{110}Pd \rightarrow {}^{110}Cd$			3.86			
$^{116}Cd \rightarrow {}^{116}Sn$		2.99	3.17			3.80
$^{124}Sn \rightarrow {}^{124}Te$	2.10		2.65			3.87
$^{128}Te \rightarrow {}^{128}Xe$	2.34	3.97	3.56	4.52	3.89	3.30
$^{130}Te \rightarrow {}^{130}Xe$	2.12	3.56	3.28	4.06	4.36	4.12
$^{136}Xe \rightarrow {}^{136}Ba$	1.76	2.30	2.54			3.38
$^{150}Nd \rightarrow {}^{150}Sm$		3.16		2.32	3.16	1.37

A compilation of extracted neutrino mass $|\langle m_\nu \rangle|$ (modulo the indicated NME), by JDV, Ejiri and Simkovic, rop in press

isotope	A [%]	$Q_{\beta\beta}$ [MeV]	$G^{0\nu}$ [10^{-14} y]	$T_{1/2}^{0\nu-exp}$ [10^{24} y]	NME	$\mid\langle m_\nu\rangle\mid$ eV [eV]	Future experiments
^{48}Ca	0.19	4.276	7.15	0.014[a]	ISM	19.1	CANDLES
					EDF	7.0	
^{76}Ge	7.8	2.039	0.71	19[b]	ISM, EDF	0.51, 0.31	GERDA
					(R)QRPA	(0.20,0.32)	
					EDF	(0.26,0.35)	
	7.8	2.039	0.71	22[c]	ISM, EDF	0.47, 0.29	-
					(R)QRPA	(0.18,0.30)	
					EDF	(0.24,0.32)	
	7.8	2.039	0.71	16[d]	ISM, EDF	0.55, 0.34	MAJORANA
					(R)QRPA	(0.22,0.35)	
					EDF	(0.28,0.38)	
^{82}Se	9.2	2.992	3.11	0.36[e]	ISM, EDF	1.88, 1.17	SuperNEMO
					(R)QRPA	(0.76,1.28)	MOON
					EDF	(1.12,1.49)	
^{100}Mo	9.6	3.034	5.03	1.0[f]	EDF	0.46	MOON
					(R)QRPA	(0.38,0.73)	AMoRE
					EDF	(0.62,1.06)	
^{116}Cd	7.5	2.804	5.44	0.17[g]	EDF	1.15	COBRA
					(R)QRPA	(1.20,2.16)	$CdWO_4$
^{130}Te	34.5	2.529	4.89	3.0[h]	ISM, EDF	0.52, 0.27	CUORE
					(R)QRPA	(0.25,0.43)	
					EDF	(0.33,0.46)	
^{136}Xe	8.9	2.467	5.13	5.7[i]	ISM, EDF	0.44, 0.23	EXO, NEXT
					(R)QRPA	(0.17,0.30)	KamLAND-Zen
^{150}Nd	5.6	3.368	23.2	0.018[j]	EDF	4.68	SuperNEMO
					(R)QRPA	(2.13,2.88)	SNO+ DCBA

a:[237], b:[36, 227, 228], c:[42], d:[229, 230], e:[38, 234, 235], f:[38, 234], g:[238], h:[231, 232, 239], i:[40], j:[38, 240].

Lepton Number Non-Conservation

- Implies that 0ν-ββ decay occurs at some level
- There are many mechanisms which may lead to 0ν-ββ decay . Such as

  -Mass Mechanism (the usual Left-handed light neutrinos)

  - Mass mechanism for heavy neutrinos (left and/or right handed contribution)

  -Other heavy intermediate particles (SUSY R-parity violating)

  -Interference between left and right handed leptonic current ⇓

  Light neutrino mass independent contribution
- Regardless of the dominant mechanism,

  the observation of 0ν-ββ decay will imply

  -The neutrinos are Majorana particles

  -The neutrinos are massive and non degenerate
- In our days, however, we demand much more!

- But, how can one extract the neutrino mass scale from the data?
The nuisance of many mechanisms

- The analysis of the data is more complicated since , as we have mentioned, there exist many mechanisms that can interfere
- Suppose that the nuclear ME are reliable, the experiments get even below 50 meV and we do not see 0ν ββ-decay. Can we rule out the inverted hierarchy scenario?

No, if observed only in one nucleus. There could be cancellations!

Perhaps yes, if observed in many targets

II: Extracting <m$_\nu$> from the life time in the presence of many mechanisms:

Crucial ingredient: The dependence of the nuclear Matrix Elements on the target

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}_{01} \left\{ |X_L|^2 + |X_R|^2 - \tilde{C}'_1 X_L X_R + \ldots \right.$$

$$+\tilde{C}_2 |\lambda| X_L cos\psi_1 + \tilde{C}_3 |\eta| X_L cos\psi_2 + \tilde{C}_4 |\lambda|^2 + \tilde{C}_5 |\eta|^2$$

$$\left. +\tilde{C}_6 |\lambda||\eta| cos(\psi_1 - \psi_2) + Re(\tilde{C}_2 \lambda X_R + \tilde{C}_3 \eta X_R) \right\},$$

Left handed contributions only: X_L

- $\eta_\nu = \langle m_\nu \rangle / m_e$, Ω_ν : The usual nuclear ME
- η_N , Ω_N : Heavy neutrino (Left handed currents)
- η_{SUSY} , Ω_{SUSY} :Supersymmetric contribution
- $X_L = \eta_\nu \Omega_\nu + \eta_N \Omega_N + \eta_{SUSY} \Omega_{SUSY}$

Ia: The see-saw mechanism; The mixing matrix is more complicated

In the presence of right handed neutrino

$$U = \begin{pmatrix} U^{11} & U^{12} \\ U^{21} & U^{22} \end{pmatrix} \quad , U^{12} \ll 1 \quad , U^{21} \ll 1 \Rightarrow$$

$$\begin{pmatrix} \nu_L^0 \\ \nu_L^{0c} \end{pmatrix} = \begin{pmatrix} U^{11} & U^{12} \\ U^{21} & U^{22} \end{pmatrix} \begin{pmatrix} \nu_L \\ N_L \end{pmatrix}$$

$$\nu_L^0 = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L})$$

$$\nu_L^{0c} = (\nu_{eL}^c, \nu_{\mu L}^c, \nu_{\tau L}^c) \Longleftrightarrow$$

right handed neutrino.

The week electron neutrino states have six components: 3 light and 3 heavy

Thus

$$\nu^0_{eL} = \sum_{j=1}^{3} U^{11}_{ej} \nu_{jL} + \sum_{j=1}^{3} U^{12}_{ej} N_{jL}$$

$$\nu^{c0}_{eL} = \sum_{j=1}^{3} U^{21}_{ej} \nu_{jL} + \sum_{j=1}^{3} U^{22}_{ej} N_{jL}$$

In the absence of $\nu^{0c}_L \Rightarrow$

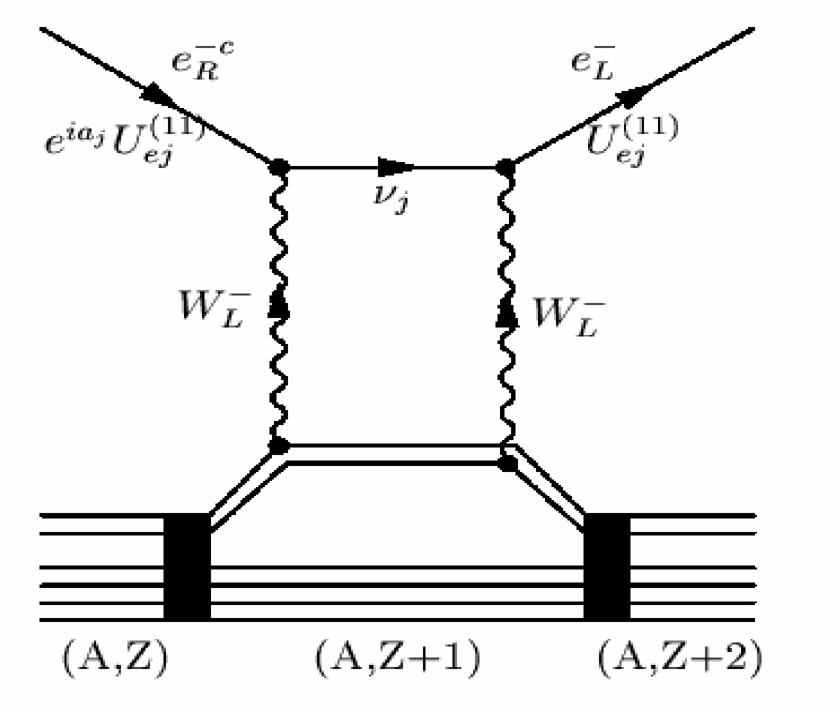
$$U = U^{11} = U_{MNS},$$

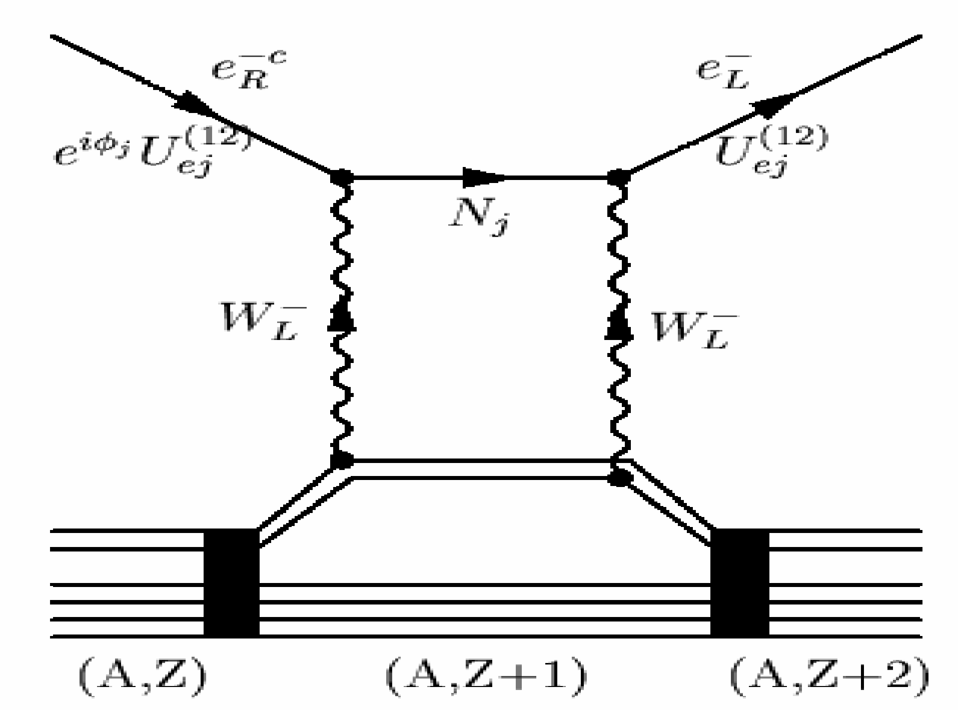
$$U^{12} = U^{21} = U^{22} = 0$$

IIa: Mass terms: light & heavy neutrinos

$$< m_\nu > \; = \sum_j^3 (U_{ej}^{(11)})^2 \, \xi_j \, m_j$$

$$\eta_N^L = \sum_j^3 (U_{ej}^{(12)})^2 \; \Xi_j \, \frac{m_p}{M_j}$$

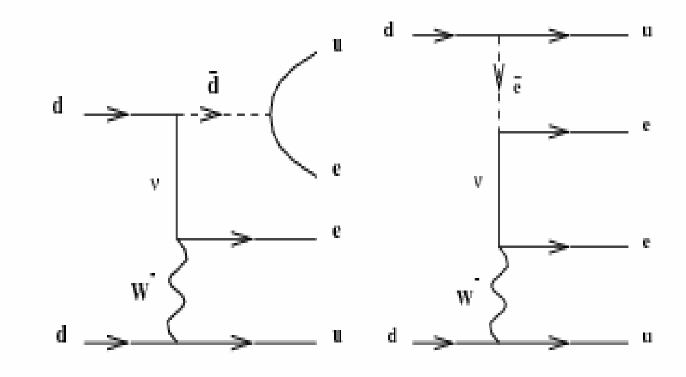




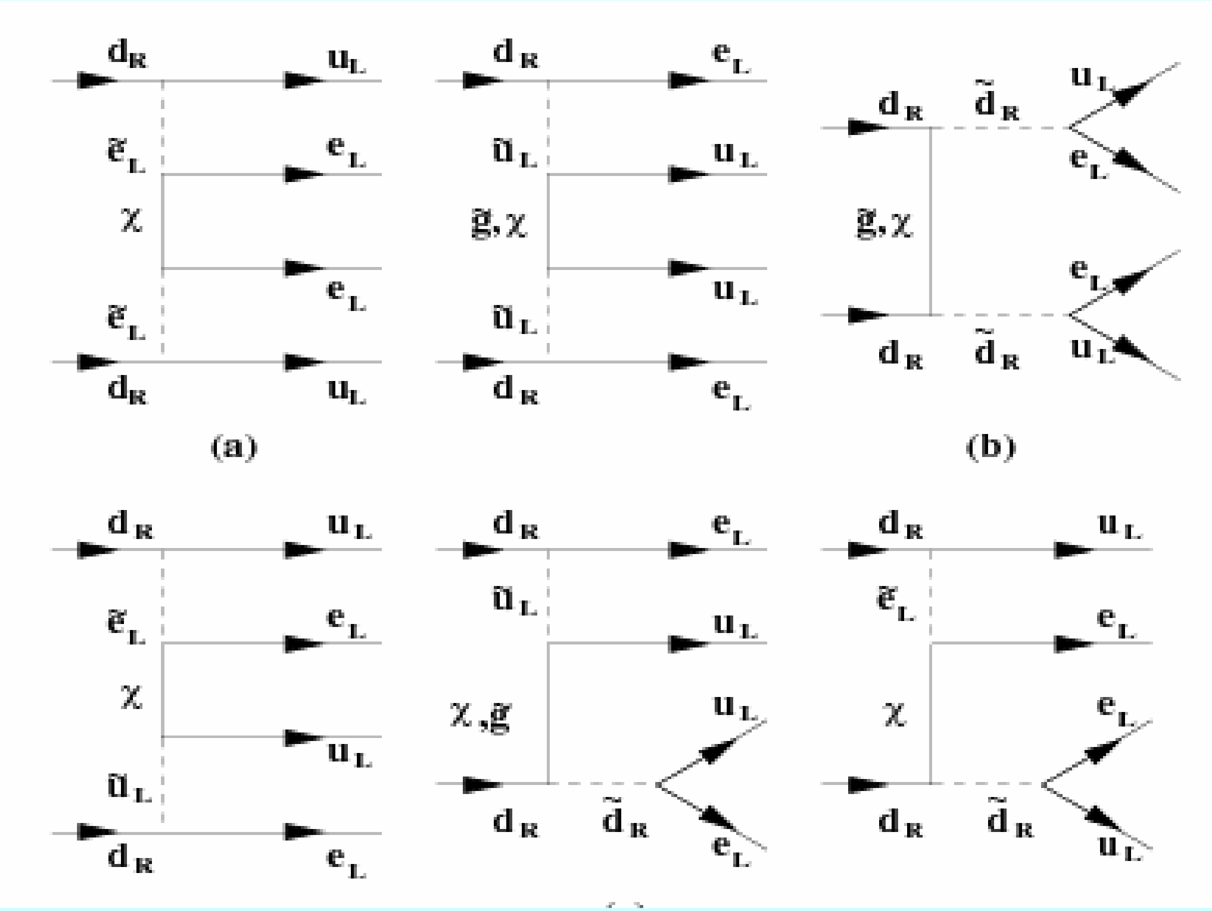
IIb: SUSY Contributions (interference with left handed neutrinos): $\eta_{susy}=\eta_{\lambda'}=(\lambda'_{111})^2\eta_{SPT}$

Light mediator →

Like λ term in connection with right handed currents



Heavy Intermediate particles



Nuclear ME for various Mechanisms in SQRPA (J.D.V, Ejiri, Simkovic, arXiv:1205.0649)

Nucleus	NN pot.	g_A^{eff}	$\lvert M'^{0\nu}_{\nu}\rvert$	$\lvert M'^{0\nu}_{N}\rvert$	$\lvert M'^{0\nu}_{\lambda'}\rvert$	$\lvert M'^{0\nu}_{\tilde{q}}\rvert$
^{76}Ge	Argonne	1.25	5.44	265	700	718
		1.00	4.39	196	461	476
	CD-Bonn	1.25	5.82	412	596	728
		1.00	4.69	317	393	483
^{82}Se	Argonne	1.25	5.29	263	698	710
		1.00	4.18	193	455	465
	CD-Bonn	1.25	5.66	408	594	720
		1.00	4.48	312	388	472
^{100}Mo	Argonne	1.25	4.79	260	690	683
		1.00	3.91	192	450	449
	CD-Bonn	1.25	5.15	404	589	691
		1.00	4.20	311	384	455
^{130}Te	Argonne	1.25	4.18	240	626	620
		1.00	3.34	177	406	403
	CD-Bonn	1.25	4.70	385	540	641
		1.00	3.74	294	350	416
^{136}Xe	Argonne	1.25	2.75	160	428	418
		1.00	2.19	117	277	271
	CD-Bonn	1.25	3.36	172	460	459
		1.00	2.61	125	297	297

Extraction of lepton violating parameters for one mechanism (J.D.V, Ejiri, Simcovic, arXiv:1205.0649)

nucl.	$T_{1/2}^{0\nu-exp}$ [years]	$\lvert\langle m_\nu\rangle\rvert$ [eV]	$\lvert\eta_N^{L,R}\rvert$ $\times 10^9$	$\lvert\eta_{\lambda'}\rvert$ $\times 10^9$	λ'_{111} $\times 10^4$	$\lvert\eta_{\tilde{q}}\rvert$ $\times 10^9$	$\lambda'_{111}\lambda'_{111}$ $\times 10^6$	$\lambda'_{112}\lambda'_{121}$ $\times 10^7$	$\lambda'_{113}\lambda'_{131}$ $\times 10^8$
^{76}Ge	$1.9\ 10^{25}$	0.23	6.2	4.3	1.2	3.5	6.3	3.3	1.4
^{82}Se	$3.2\ 10^{23}$	0.85	23.	16.	2.3	13.	24.	12.	5.1
^{100}Mo	$1.0\ 10^{24}$	0.41	10.	7.1	1.5	6.0	11.	5.7	2.4
^{130}Te	$3.0\ 10^{24}$	0.27	6.4	4.5	1.2	3.8	6.9	3.6	1.5
^{136}Xe	$5.7\ 10^{24}$	0.26	10.	3.7	1.1	3.8	6.8	3.5	1.5

IIa) Extracting $<m_\nu>$ in the presence of interference in X_L: Crucial ingredient The nuclear Matrix Elements

$$X_L = \eta_\nu \Omega_\nu + \eta_N^L \Omega_N + \eta_{SUSY} \Omega_{SUSY}$$

with Ω_ν , Ω_N , Ω_{SUSY} the nuclear matrix elements,

η_ν , η_N^L , η_{SUSY} lepton violating parameters:

$$\eta_\nu = \frac{<m_\nu>}{m_e} \ , < m_\nu > \ = \ \sum_k^3 \ (U_{ek}^{(11)})^2 \ e^{i\alpha_k} \ m_k$$

$$\eta_N^L \ = \ \sum_k^3 \ (U_{ek}^{(12)})^2 \quad e^{i\Phi_k} \ \frac{m_p}{M_k}$$

with α_k, Φ_k Malorana phases and

m_p (m_e) being the proton (electron) mass.

Present approach : Given data from three targets and the nuclear matrix elements

One can solve the system of equations to extract the LPV (lepton violating parameters) and hence the neutrino mass. a) LVP: relatively real

$$|\frac{m_{\beta\beta}}{m_e}\Omega_{\nu}(i)+\eta_N\Omega_N(i)+\eta_{\text{SUSY}}\Omega_{\text{SUSY}}(i)| = \frac{1}{\sqrt{T_i\,G_i}},\ i=1,2,3$$

Input: Nuclear matrix elements and phase space factors:

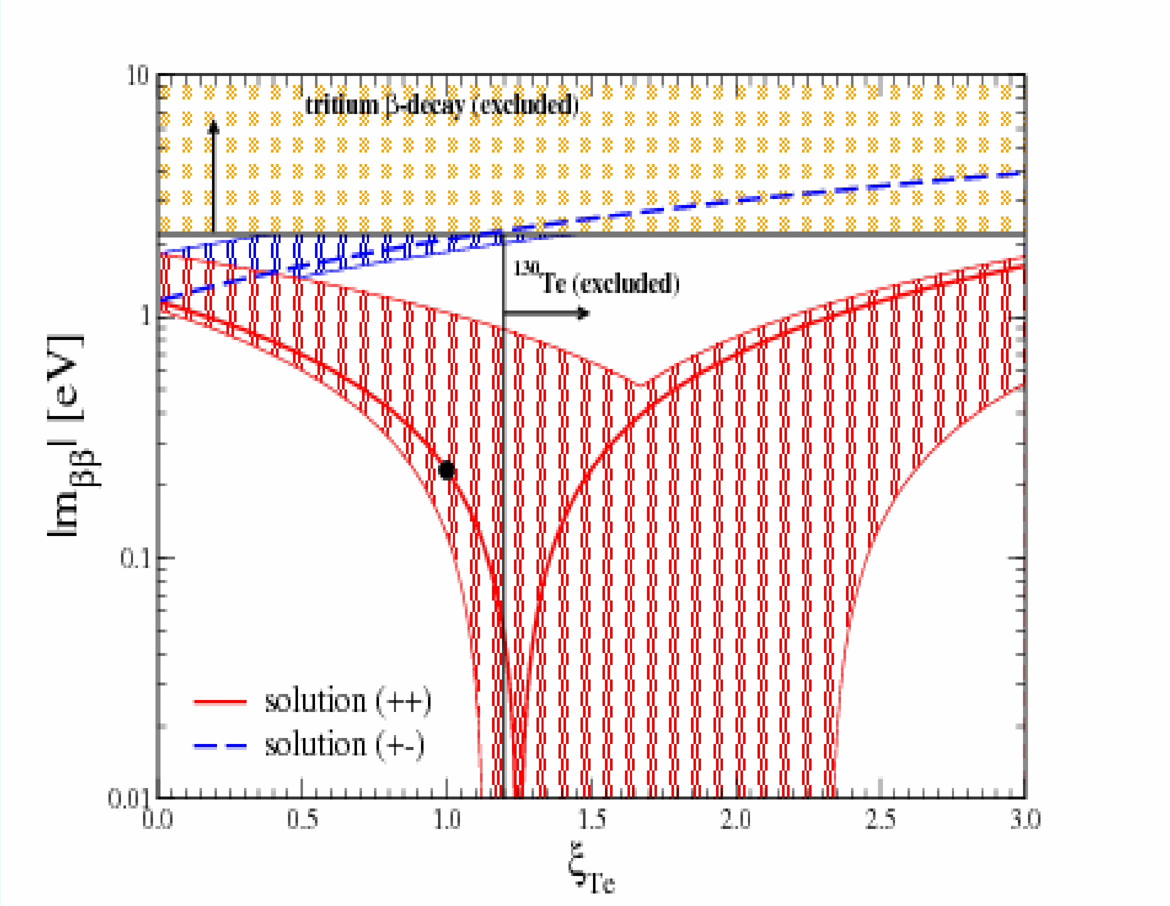
TABLE I: Averaged $0\nu\beta\beta$-decay NMEs and their variance σ (in parentheses) calculated with the Selfconsistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA). The Coupled Cluster Method (CCM) short-range correlations calculated with CD-Bonn potential are taken into account [16]. $g_A = 1.25$.

Nucl. trans.	$G^{0\nu}(E_0, Z)$ $[y^{-1}]$	Ω_ν	Ω_N	$\Omega_{SUSY} = \Omega_{\lambda'}$
^{76}Ge$\rightarrow^{76}$Se	7.98×10^{-15}	5.24(0.52)	363(44)	525(66)
^{100}Mo$\rightarrow^{100}$Ru	5.73×10^{-14}	4.89(0.22)	392(11)	550(35)
^{130}Te$\rightarrow^{130}$Xe	5.54×10^{-14}	4.53(0.23)	362(23)	511(33)

Two Mechanisms: light and heavy neutrino

Targets Ge ($T_{1/2}=2.23_{-0.31}^{+0.44}$ x10^{25}y) and Te (variable). Faessler-Simkovic-Vergados: PRD,82 (2010)

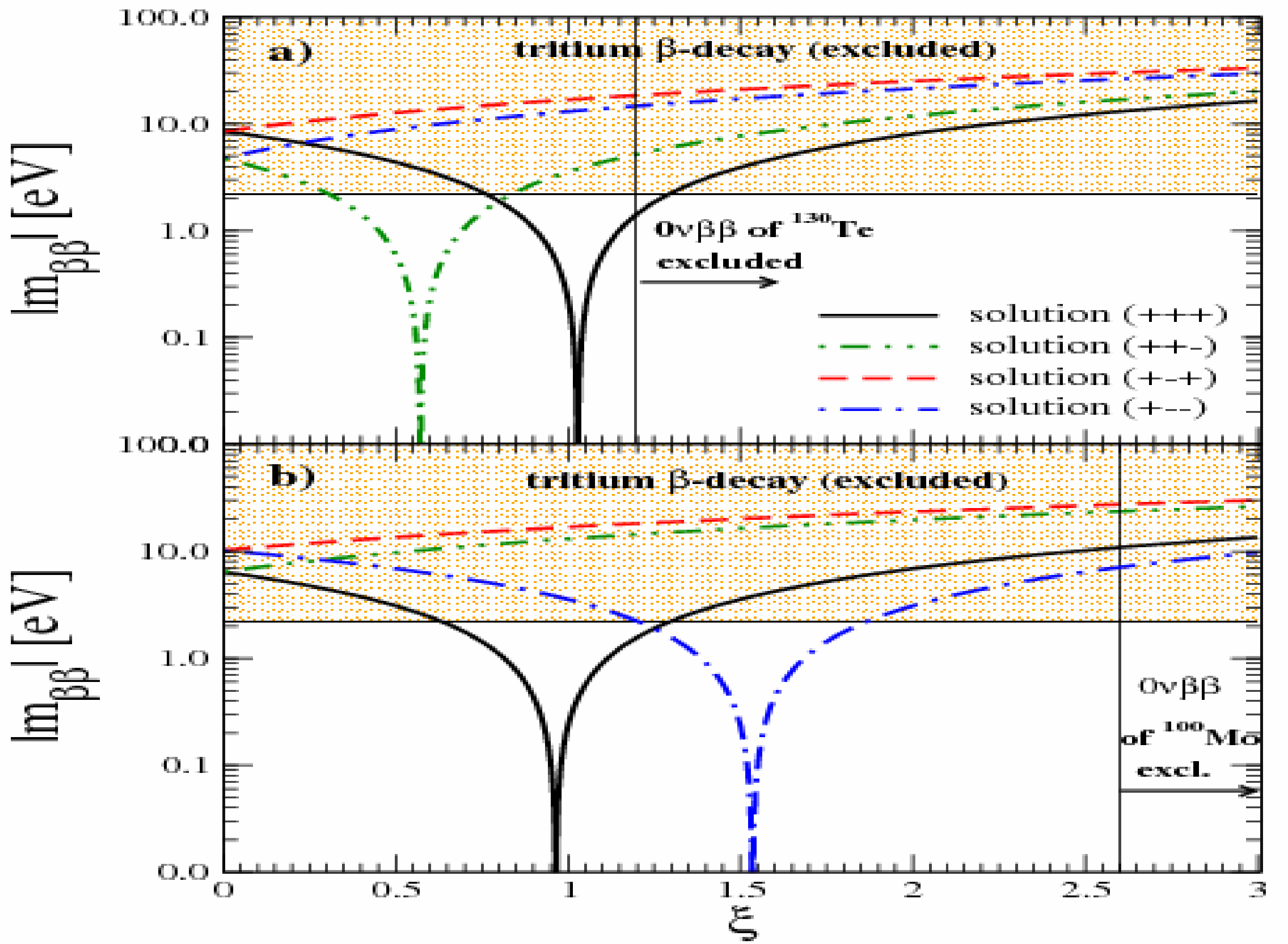
$$\xi_2 = \frac{|M_1^{\nu}|\sqrt{T_1\, G_1}}{|M_2^{\nu}|\sqrt{T_2\, G_2}},$$



Three Mechanisms: light and heavy ν and SUSY

Targets Ge ($T_{1/2}=2.23_{-0.31}^{+0.44}$ x10^{25}y) and Te (fixed $\xi_{Te}=1$ lower, variable upper), Mo (fixed $\xi_{Mo}=1$ upper, variable lower). FSV

$$\xi_2 = \frac{|M_1^{\nu}|\sqrt{T_1\, G_1}}{|M_2^{\nu}|\sqrt{T_2\, G_2}},$$



IIc) Lepton violating parameters η_ν & η_λ, not relatively real (phase α) Tuebingen-Trieste-bratislava-Ioannina:arXiv:1103.2434 (hep-ph)

- Need three targets
- Lepton violating parameters are severely constrained

1) Complex case: Extraction of $|\eta_\nu|$ (solid) and $|\eta_{\lambda'}|$ (dashed) from the data on three targets.

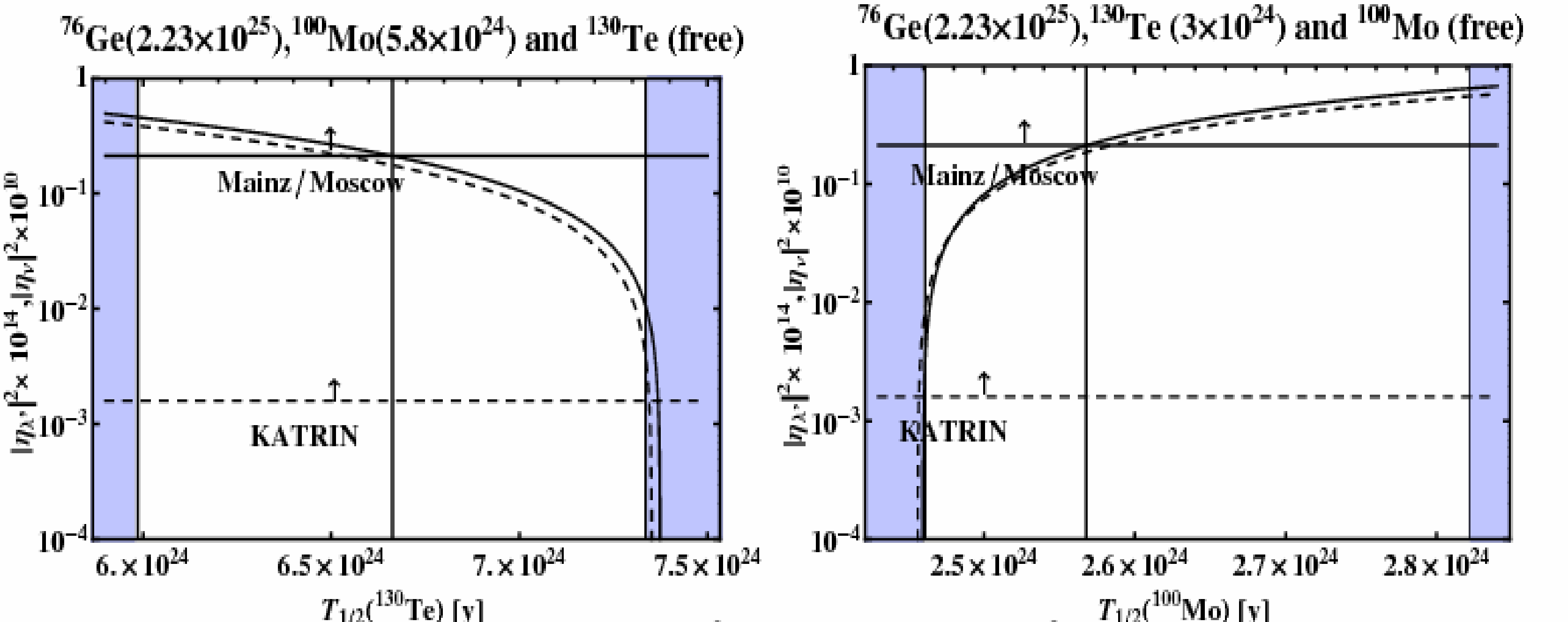


Figure 10: The values of the rescaled parameters $|\eta_\nu|^2$ (thick line) and $|\eta_{\lambda'}|^2$ (dashed lined), obtained as solutions of the system of equations (4.2) for fixed values of $T^{0\nu}_{1/2}(^{76}Ge)$ and $T^{0\nu}_{1/2}(^{100}Mo)$ and values of $T^{0\nu}_{1/2}(^{130}Te)$ lying in a specific interval. The physical allowed regions correspond to the areas shown in white, while the areas shown in gray are excluded. The horizontal solid (dashed) line corresponds to the upper limit [44, 45] $|<m>| < 2.3$ eV (prospective upper limit [45] $|<m>| < 0.2$ eV). See text for details.

2) Complex case: Extraction of $|\eta_\nu|$ (solid) and $|\eta_{\lambda'}|$ (dashed) from the data on three targets

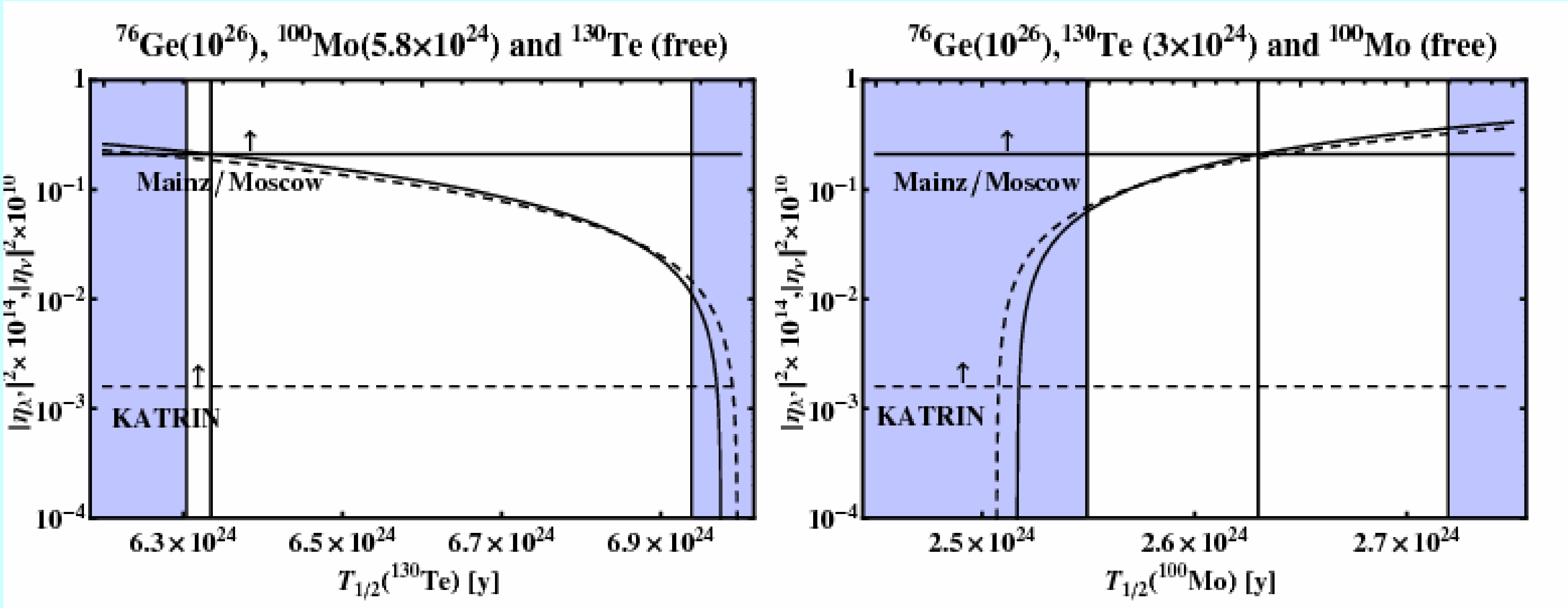


Figure 10: The values of the rescaled parameters $|\eta_\nu|^2$ (thick line) and $|\eta_{\lambda'}|^2$ (dashed lined), obtained as solutions of the system of equations (4.2) for fixed values of $T^{0\nu}_{1/2}(^{76}Ge)$ and $T^{0\nu}_{1/2}(^{100}Mo)$ and values of $T^{0\nu}_{1/2}(^{130}Te)$ lying in a specific interval. The physical allowed regions correspond to the areas shown in white, while the areas shown in gray are excluded. The horizontal solid (dashed) line corresponds to the upper limit [44, 45] $|<m>| < 2.3$ eV (prospective upper limit [45] $|<m>| < 0.2$ eV). See text for details.

3) Complex case: Extraction of $|\eta_\nu|$ (solid) and $|\eta_{\lambda'}|$ (dashed) from the data on three targets

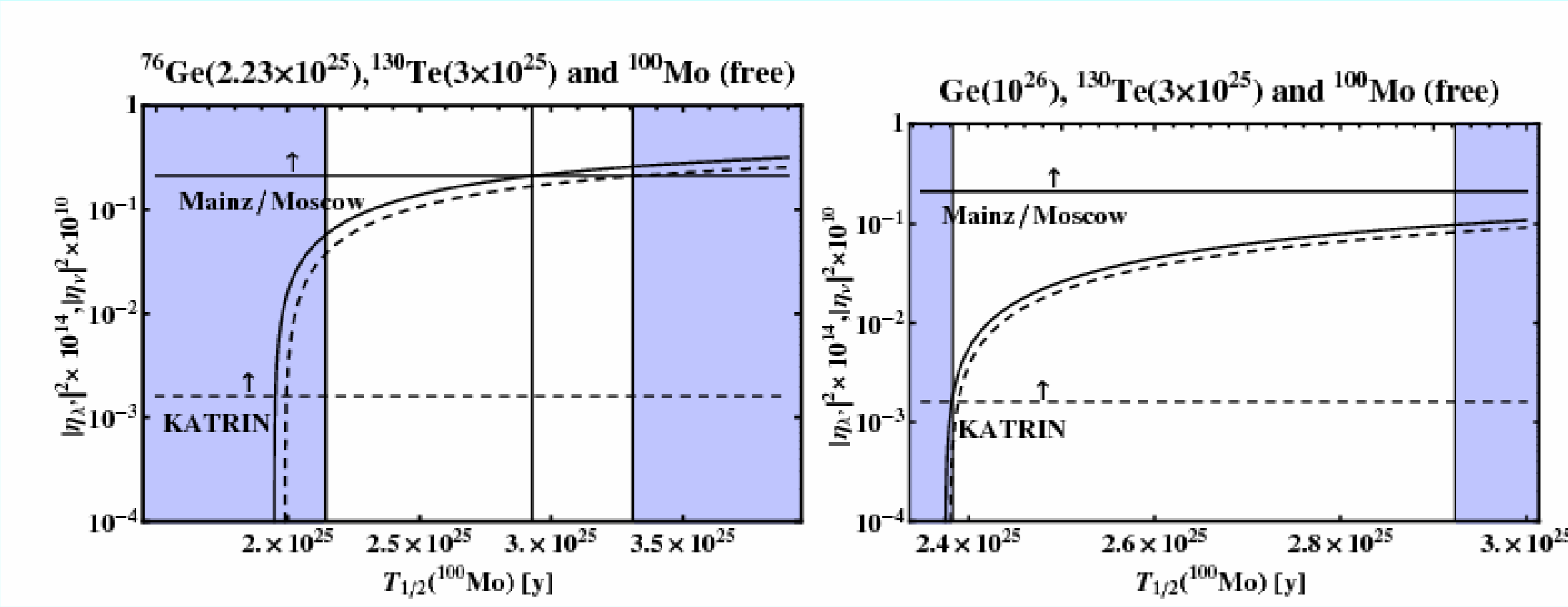
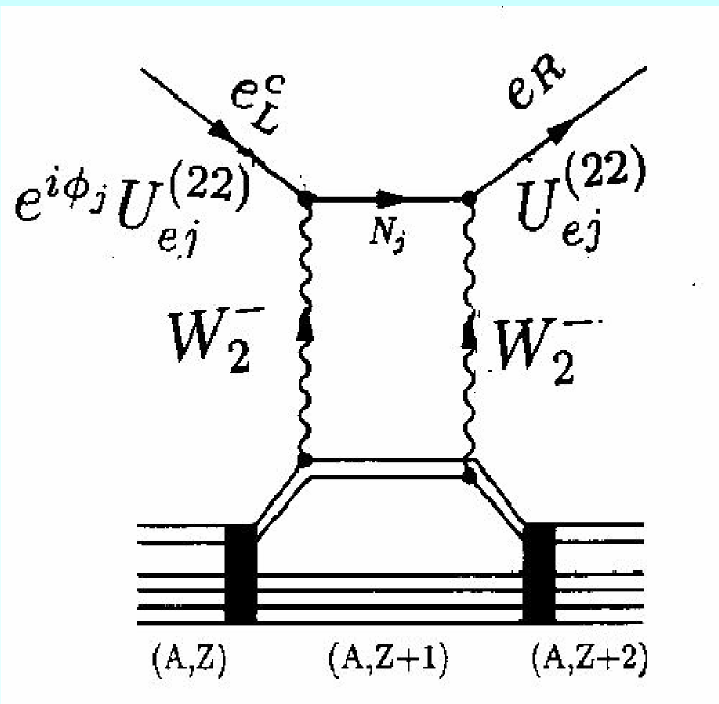


Figure 10: The values of the rescaled parameters $|\eta_\nu|^2$ (thick line) and $|\eta_{\lambda'}|^2$ (dashed lined), obtained as solutions of the system of equations (4.2) for fixed values of $T^{0\nu}_{1/2}(^{76}Ge)$ and $T^{0\nu}_{1/2}(^{100}Mo)$ and values of $T^{0\nu}_{1/2}(^{130}Te)$ lying in a specific interval. The physical allowed regions correspond to the areas shown in white, while the areas shown in gray are excluded. The horizontal solid (dashed) line corresponds to the upper limit [44, 45] $|<m>| < 2.3$ eV (prospective upper limit [45] $|<m>| < 0.2$ eV). See text for details.

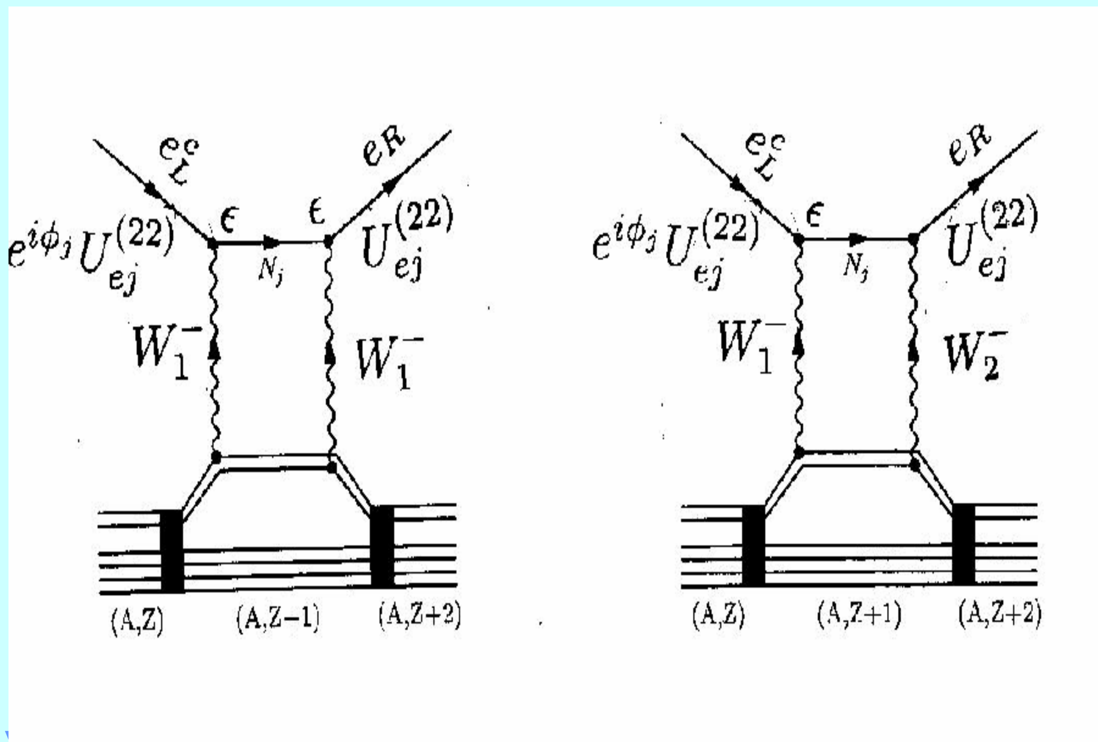
III: Mass term in right handed currents (nuclear ME similar)

$$\eta_N^R = (\epsilon^2 + \kappa^2 + c_0 \epsilon \kappa) \sum_j^3 (U_{ej}^{(22)})^2 \; \Xi_j \, \frac{m_p}{M_j}$$

Heavy R Boson : κ



Mixing L and R Bosons: ε



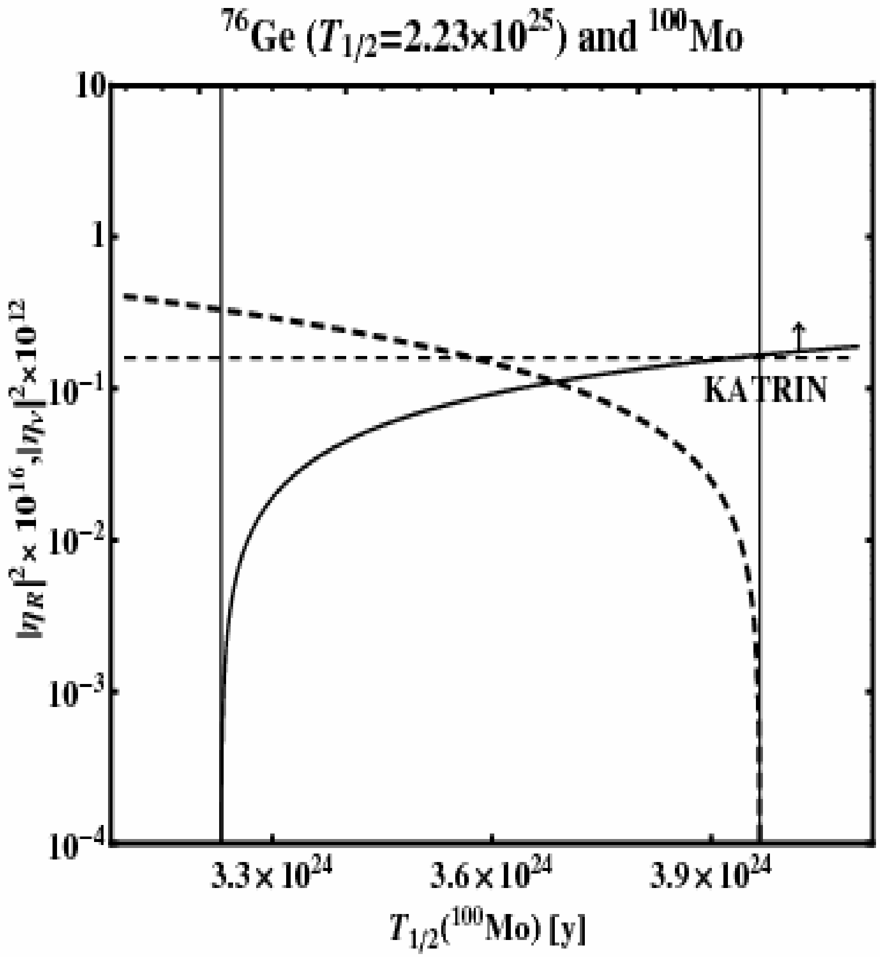
Assume: All 4 LVP, relatively real.

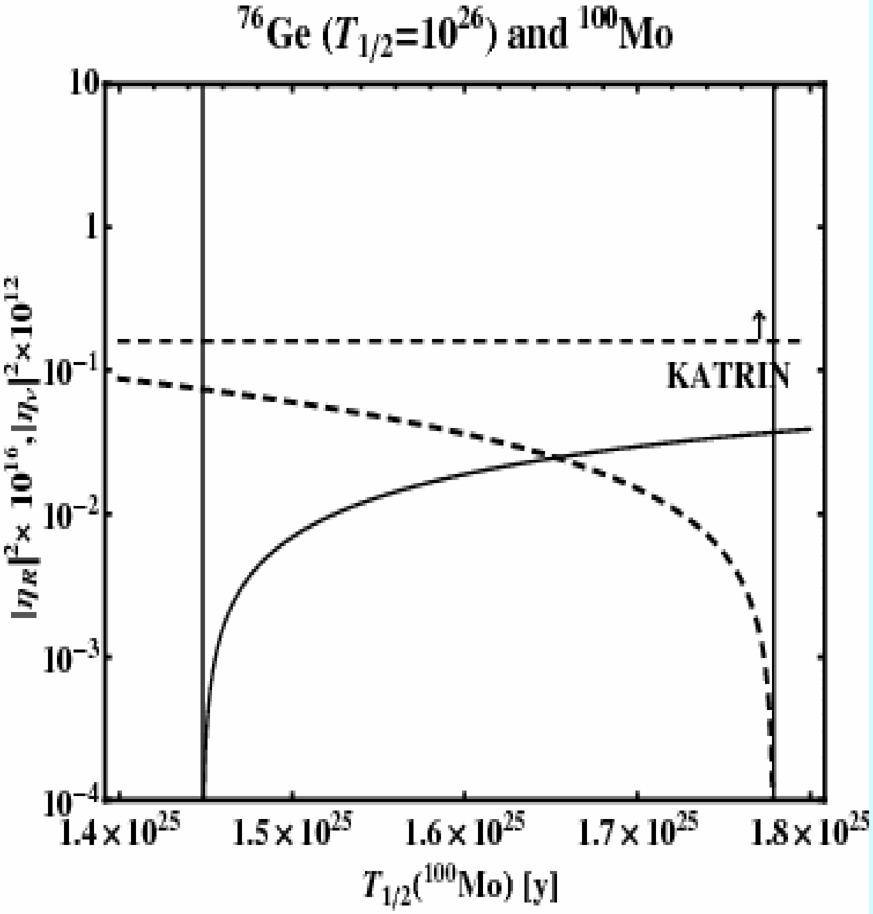
Data from at least four targets

Solve the 4 non linear equations:

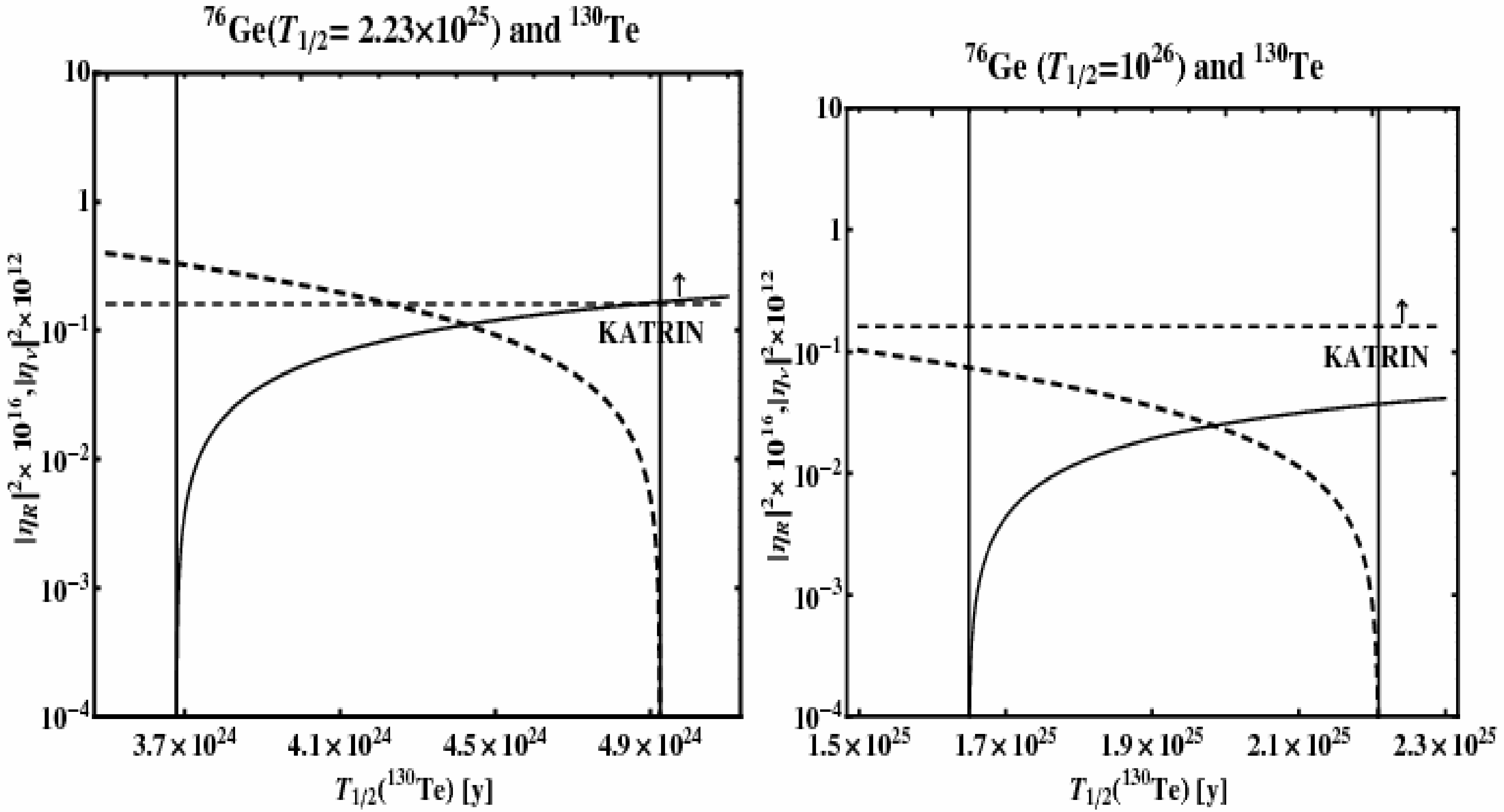
$$\left|\Omega_{\nu}(i)\eta_{\nu}+\Omega_{N}(i)\eta_{N}+\Omega_{SUSY}(i)\eta_{SUSY}\right|^{2}+\left|\Omega_{N}(i)\eta_{N}^{R}\right|^{2}=1/\left(T_{1/2}^{0\nu}(i)G^{0\nu}(i)\right),\quad i=1,2,3,4$$

1) Extraction of η_ν (solid) and η_R (dashed): Ge-Mo. The space outside the vertical bars is excluded

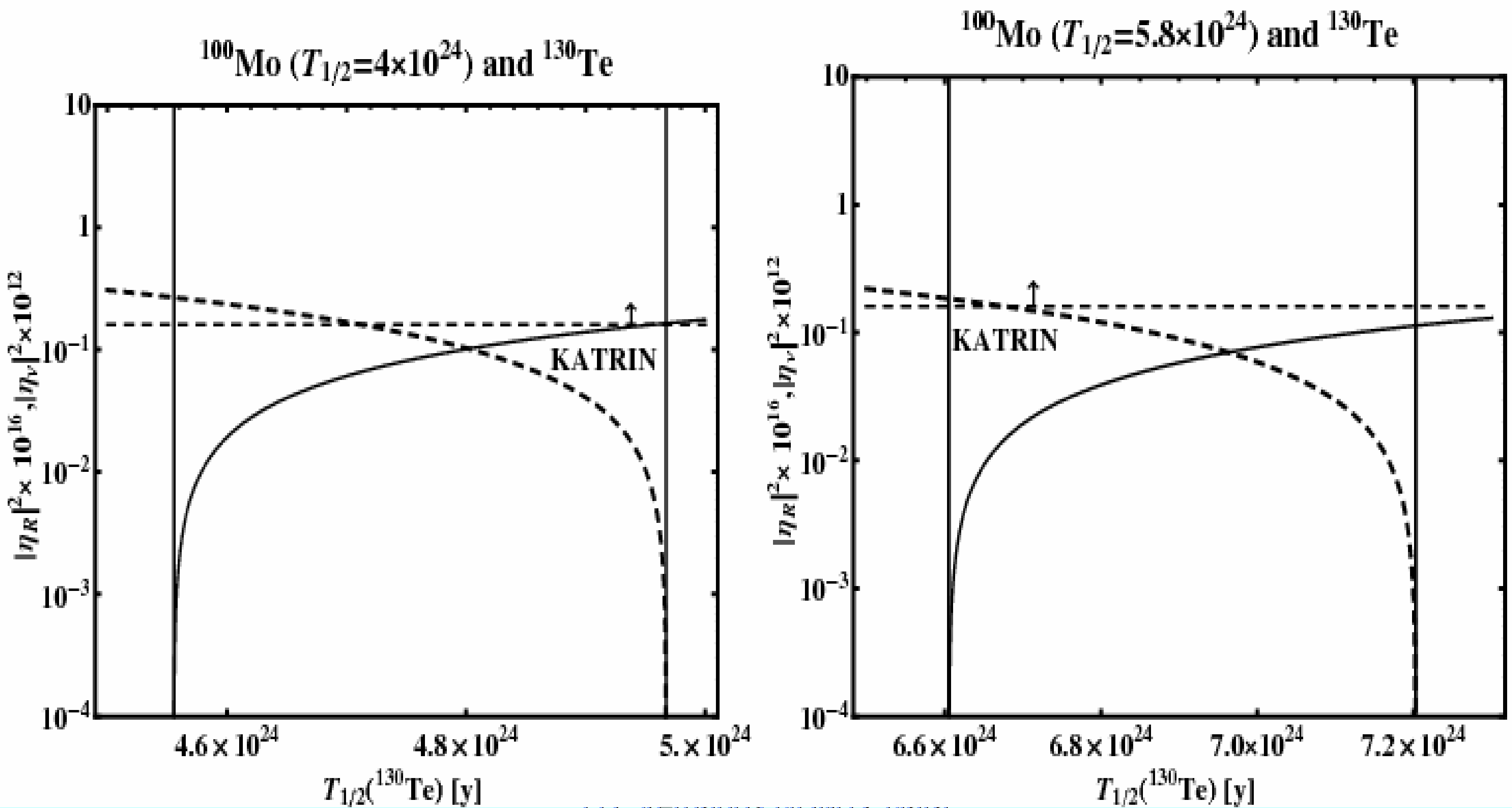




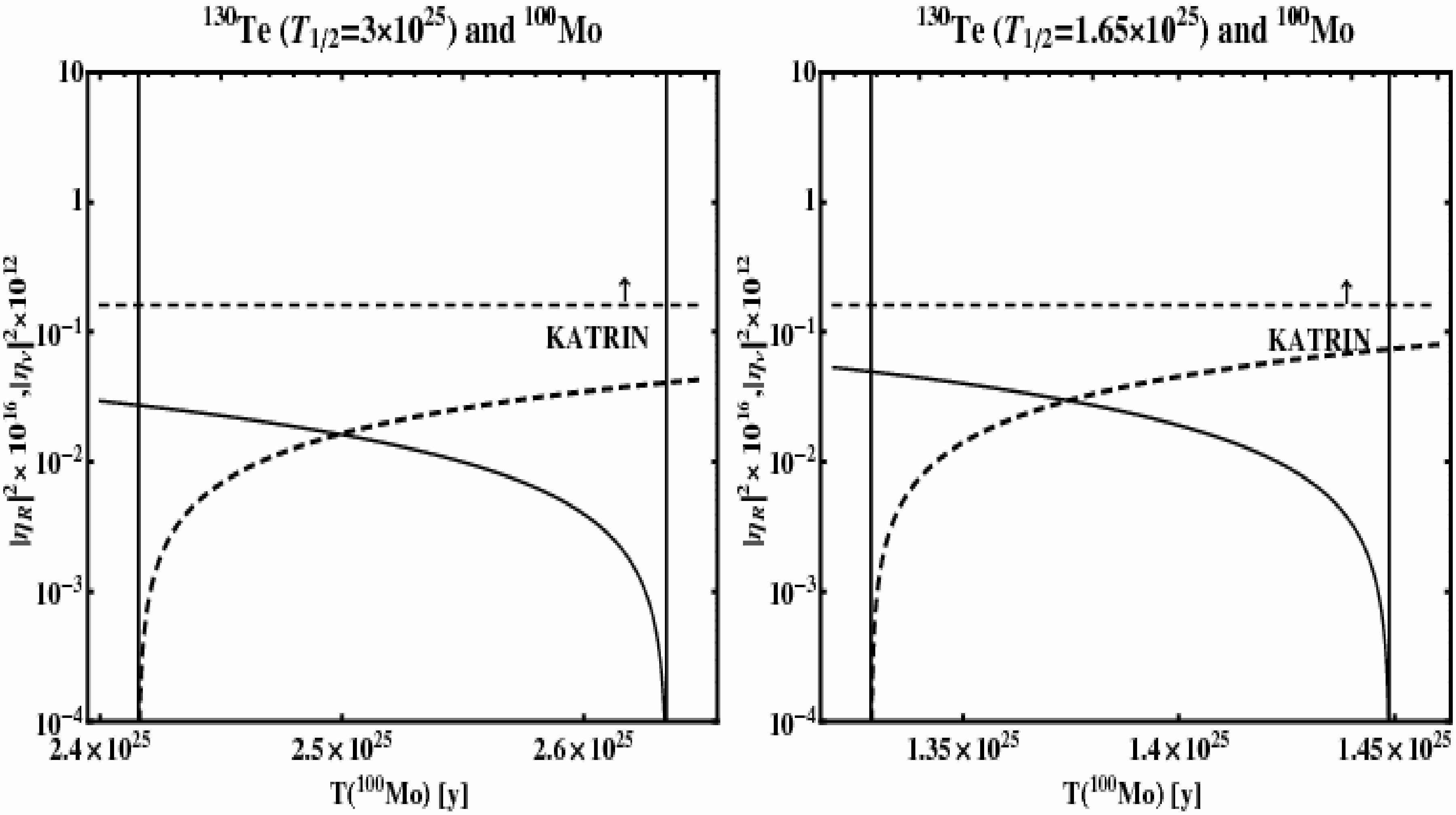
2) Extraction of η_ν (solid) and η_R (dashed): Ge-Te. The space outside the vertical bars is excluded



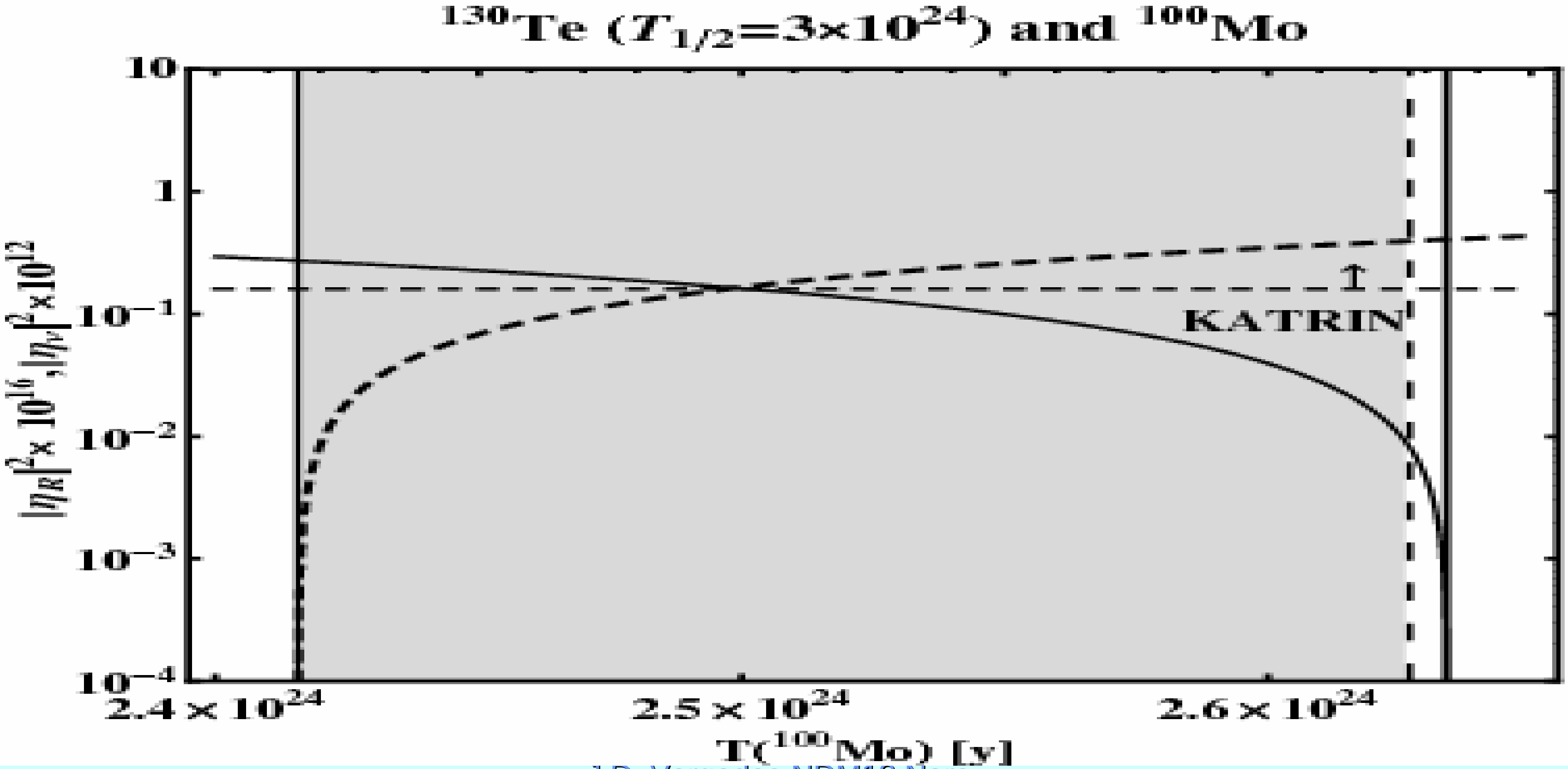
3) Extraction of η_ν (solid) and η_R (dashed): Mo-Te. The space outside the vertical bars is excluded



4) Extraction of η_ν (solid) and η_R (dashed): Te-Mo. The space outside the vertical bars is excluded



5) Extraction of η_ν (solid) and η_R (dashed): Te-Mo. The space outside the vertical bars is excluded. The minimum value of $T_{1/2}$ (Te) was assumed.



Conclusions

- 0ν-$\beta\beta$ decay is a very important process.
- It is still elusive 70 years after first proposed
- If observed it will demonstrate

-That the neutrinos are Majorana particles

-That there exist lepton number violating process (as it must have been the case in the first stages of the universe)

- This exciting observation will not by itself establish the absolute scale of neutrino mass. It will not solve the neutrino hierarchy problem
- Only its observation in a variety of targets, employing different methods and techniques, may do so!
- Provided that all nuclear ME can be accurately calculated.

Encourage searching for all Lepton Violating Process and exploit each one's special features:

- $N(A,Z) \to N(A,Z+2)+e^- + e^-$ (0ν ββ-decay) Q
- $N(A,Z) \to N(A,Z-2)+e^+ + e^+$ $Q-4m_e c^2$
  (double positron emission)
- $e^-_b + N(A,Z) \to N(A,Z-2)+e^+$ $Q-2m_e c^2$
  (electron positron conversion)
- Pay attention to the special signatures of:

$$e^-_b + e^-_b + N(A,Z) \to N(A,Z-2)+2 \text{ X-rays} \quad Q$$

(Double electron capture Vergados (1982); Sujkowski and Wycech 2004, Simkovic et al 2009, many groups 2011)

Are experimenters optimists or Don Quixotes ?

Once the wise Mullah Nasrudin was seen beating a lake with a huge spoon.

Evidently in the hope of transforming the lake into gold.

When his fellow villagers teased him:

-Mullah! You surely are wasting your time!

He sternly replied:

-Imagine, though, that it works!

(Such a reward!)

Nuclear theorists are powerful calculators. Are they really problem solvers?

Once all mighty God gave 5 golden cows, made of pure gold, to be divided among the Nuclear Theorists working on $0\nu\beta\beta$ decay as follows:

- 1/3 goes to LBSM .
- 1/3 goes to QRPA
- 1/6 goes to IBM

Condition: No cow should be carved.

Obviously the powerful theorists did not know how to do this.

So they went, where else?, to Mulah Nasrudin.

He thought for a while and ordered his wife to bring into the pack their own cow, which he valued more than golden.

Now there are 6 cows in the pack. It was easy for the first two groups to get 2 each and the third to get 1.

His cow was left and his wife took it back to the stable.

Was this a fair deal?

Was it a fair deal? After the fact the nuclear theorists know the math!

- Mullah did not know how to sum infinite series, but

$$\frac{5}{3}+\frac{1}{3}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{3}+\frac{1}{3}=2$$

$$\frac{5}{6}+\frac{1}{6}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{6}+\frac{1}{6}=1$$

- THE END

This is not the end of the 0ν-$\beta\beta$ story!

- In the presence of right-handed currents
- Light Majorana neutrino contribution independent of mass: (λ , η).
- Fortunately this may be disentangled from the mass term due to different kinematics (e.g. NEMO experiment).
- One now can get constraints in a multidimensional space.

IV) Light neutrino: Left-right interference <-> Different Kinematcs

$$\nu^0_{eL} = \sum_{j=1}^{3} U^{11}_{ej}\,\nu_{jL}$$

$$\nu^{c0}_{eL} = \sum_{j=1}^{3} U^{21}_{ej}\,e^{i\alpha_j}\,\nu_{jL}$$

Two lepton violating parameters (independent of neutrino mass)

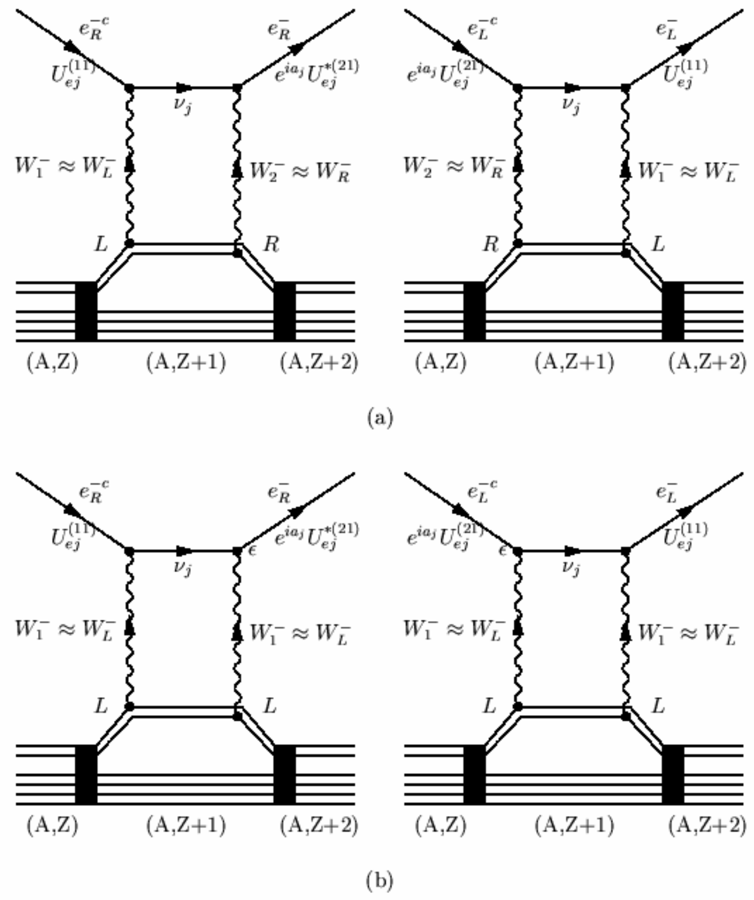
$$\eta = \tan\zeta\ \eta_{RL} \quad , \quad \lambda = \kappa\ \eta_{RL}$$

$$\eta_{RL} = \sum_{j=1}^{3} U^{11}_{ej} U^{21}_{ej} e^{i\alpha_j}$$

ζ the $W_L - W_R$ mixing angle

and

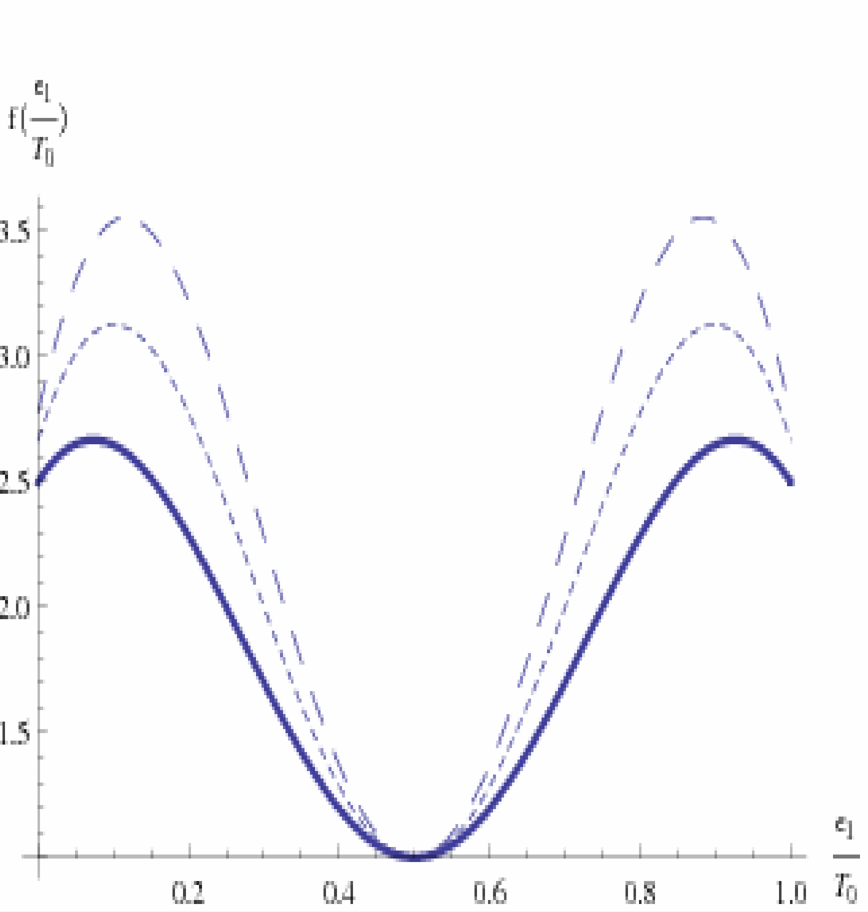
$$\kappa = \frac{m^2_{WL}}{m^2_{WR}}$$



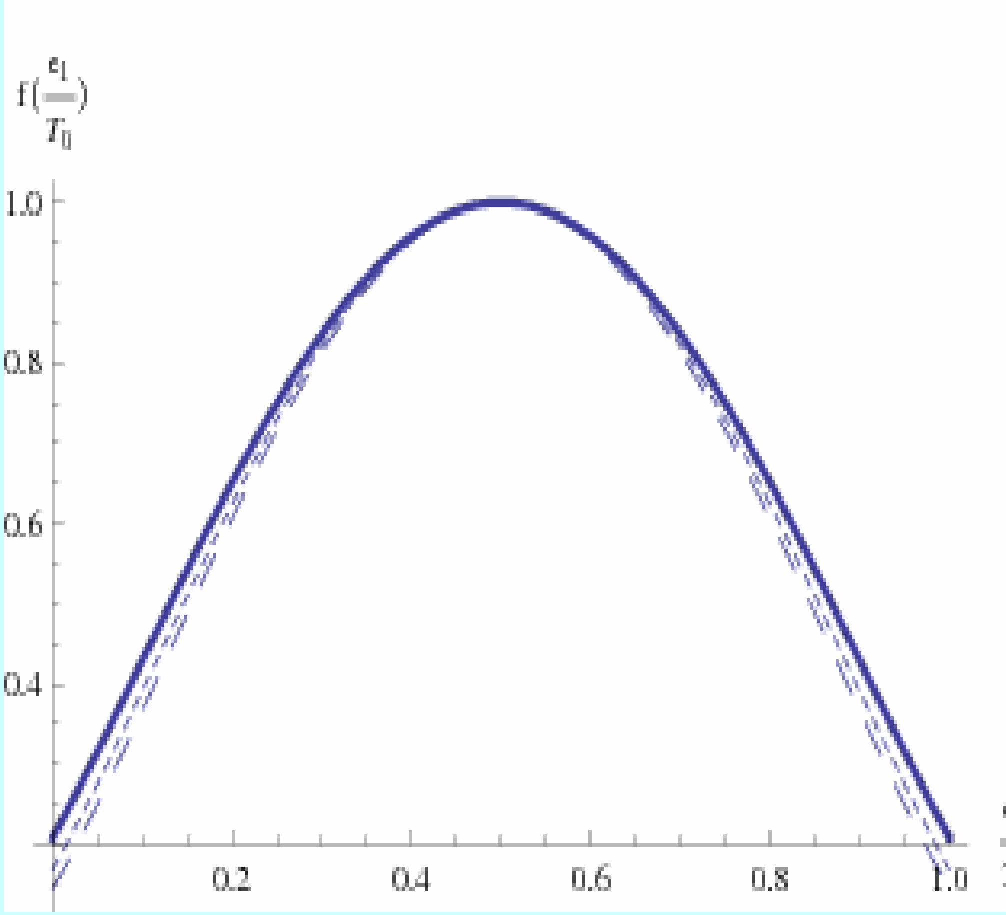
Must measure tracks, e.g. NEMO

1) The single electron spectrum

λ-term only

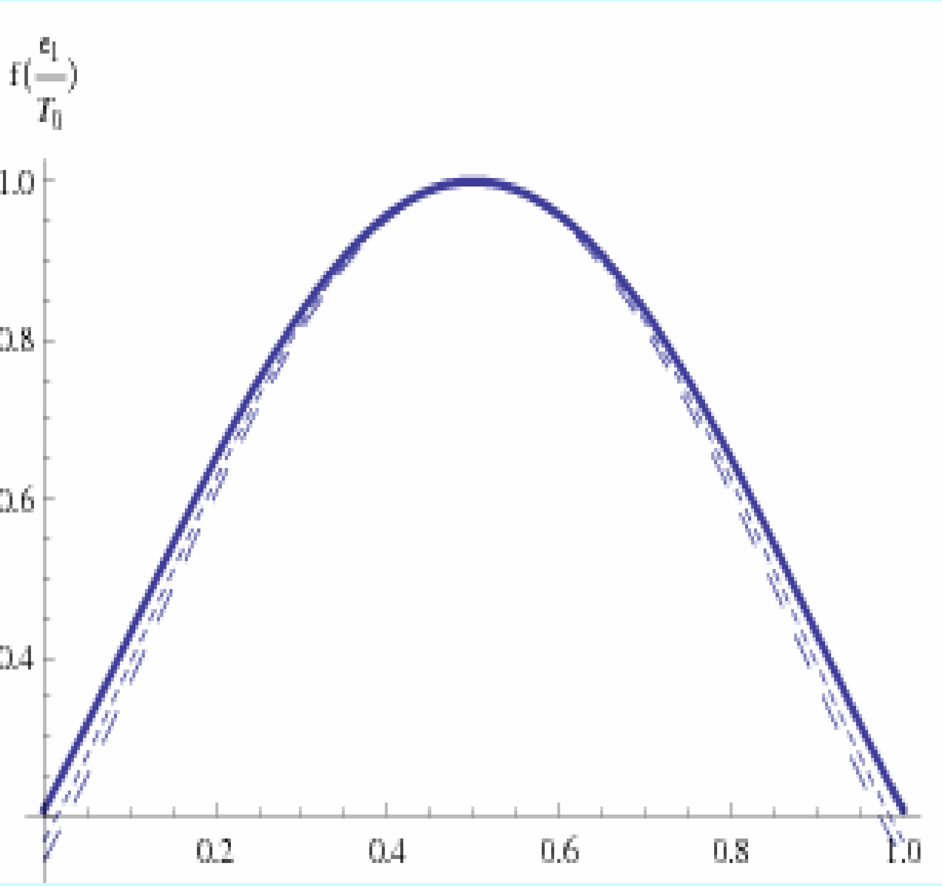


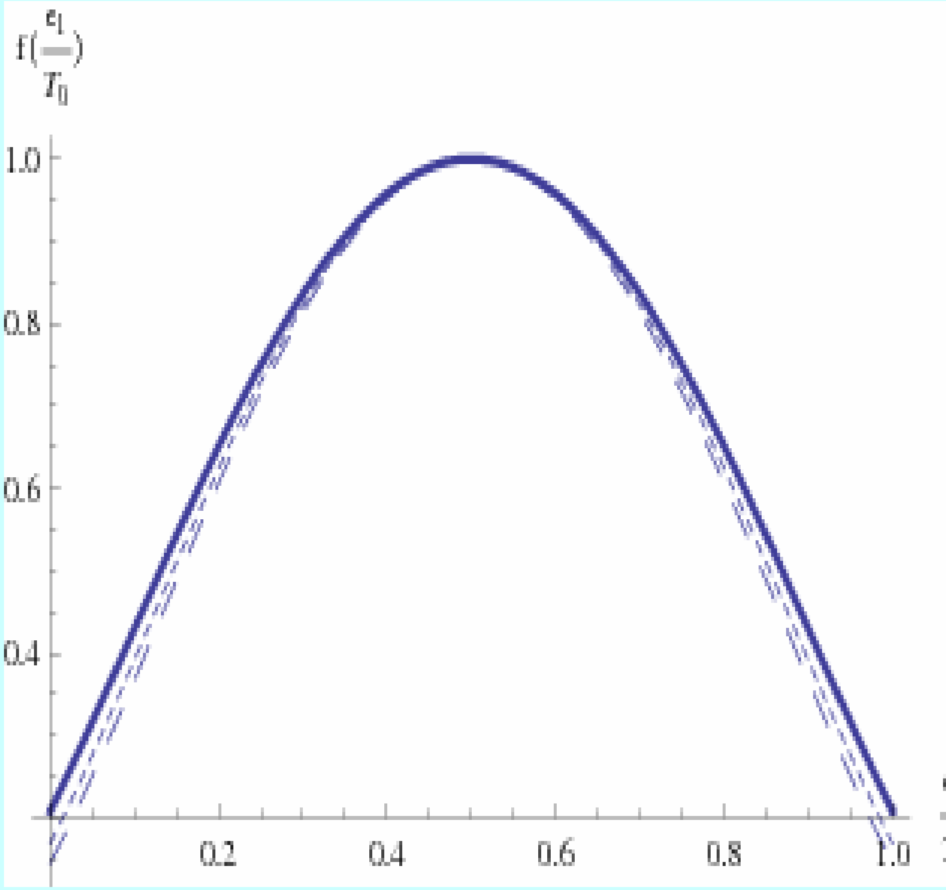
Mass-term only



2) The single electron spectrum (no visible difference)

η-term only **Mass term only**

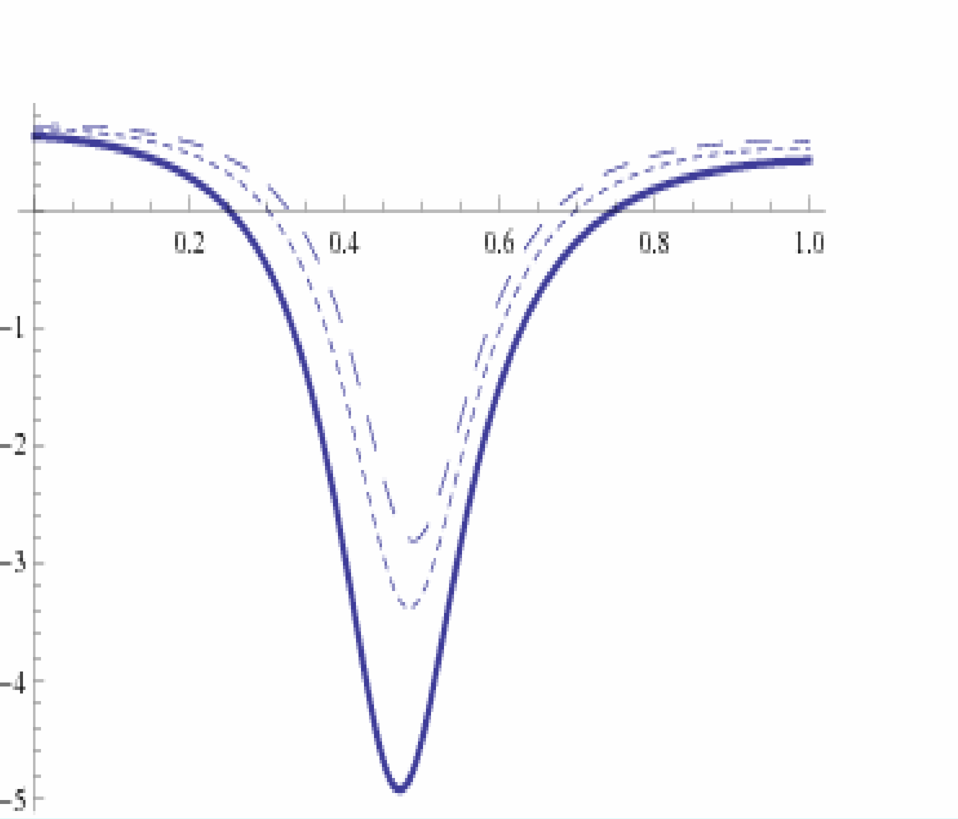


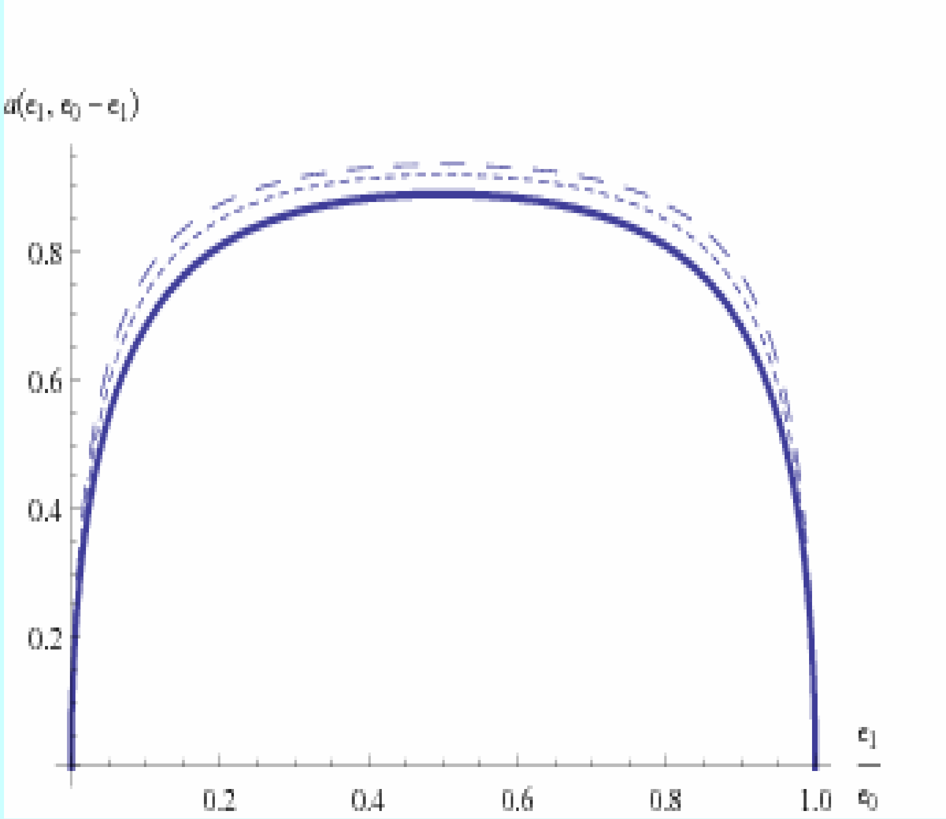


Angular correlation of the two electrons

$d\Gamma/d\xi=\Gamma_0\,(1-\alpha(\varepsilon_1,\varepsilon_2)\xi)$, $\xi=\cos\theta_{12}$

λ-term only | **Mass-term only**

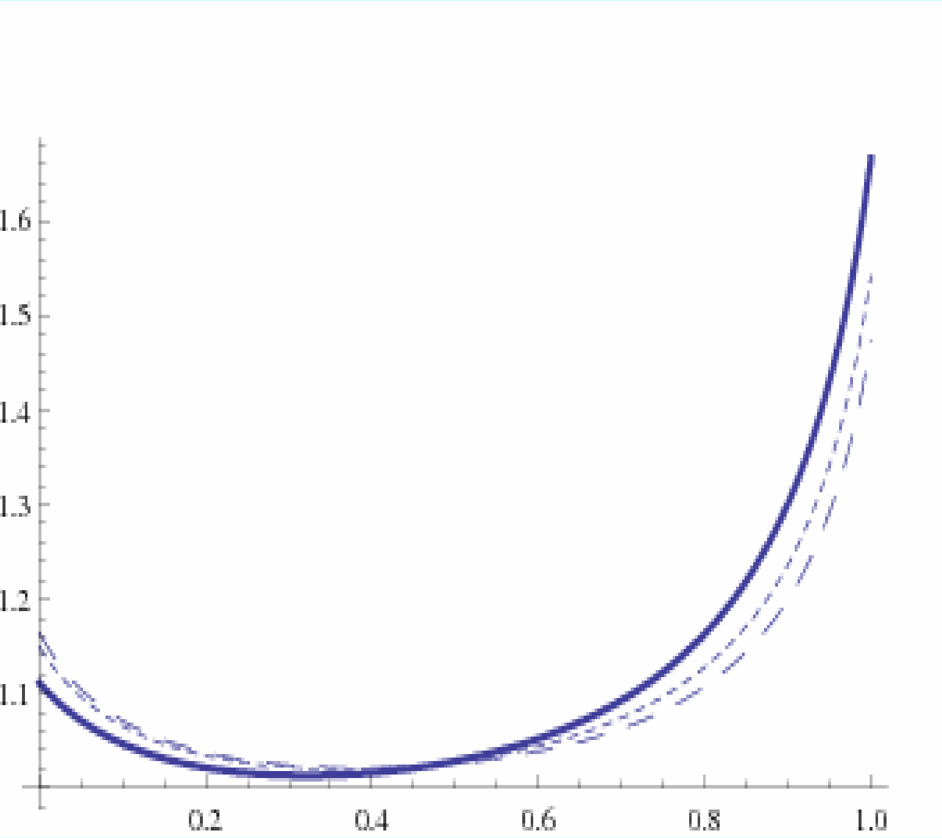




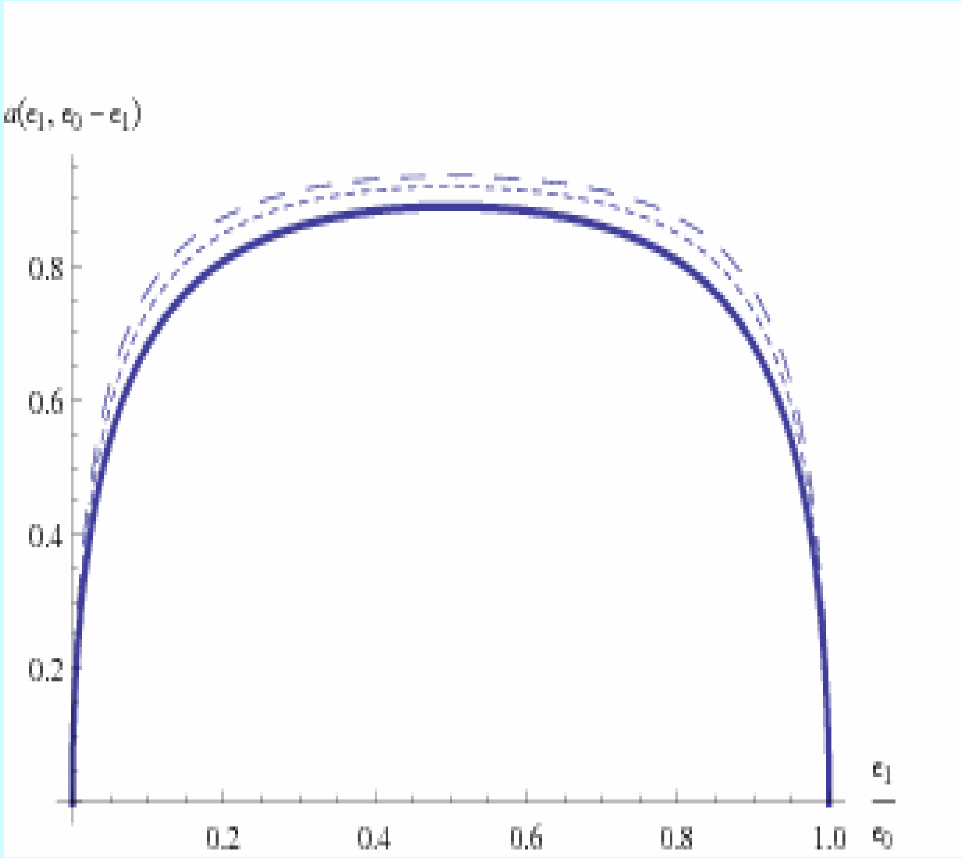
Angular correlation of the two electrons

$d\Gamma/d\xi=\Gamma_0\,(1-\alpha(\varepsilon_1,\varepsilon_2)\xi)$, $\xi=\cos\theta_{12}$

η-term only



Mass term only



Double beta decay isotopes are rare->Enriched Isotopes.

Available now :

^{48}Ca - AVLIS† (USA

^{76}Ge - Centrifuge (Russia)

^{82}Se - Centrifuge (Russia)

^{100}Mo - Centrifuge (Russia) & AVLIS† (USA)

^{116}Cd - Centrifuge (Russia) & AVLIS† (USA)

^{130}Te - Centrifuge (Russia)

^{136}Xe - Centrifuge (Russia)

^{150}Nd - AVLIS† (USA)

† Technology available at LLNL. No known production program.

2νββ - decay: Second order weak interaction allowed by the laws of physics, just too slow

Table 2: Two neutrino $\beta^-\beta^-$ decays. $Q_{\beta\beta}$: Q value in units of MeV for the $0^+ \to 0^+$ ground-state. transition, $T^{2\nu}_{1/2}$: half-life in units of 10^{20} y, and $M^{2\nu}$ in units of $(m_e)^{-1}$

.

Isotope	$Q_{\beta\beta}$ MeV	$T^{2\nu}_{1/2}$ 10^{20} y	$M^{2\nu}$	Comment
^{48}Ca	4.276	0.42 ± 0.12	0.026	a
^{76}Ge	2.039	13 ± 1	0.077	b
^{82}Se	2.992	0.96 ± 0.11	0.051	c
^{100}Mo	3.034	0.071 ± 0.0056	0.11	d
^{100}Mo	1903	6.8 ± 1.2	0.092	d
^{116}Cd	2.804	0.32 ± 0.03	0.061	e
^{128}Te	0.876	72000 ± 3000	0.013	f
^{130}Te	2.529	6.8 ± 1.2	0.014	g
^{136}Xe	2.467	21 ± 2.5	0.01	h
^{150}Nd	3.368	0.092 ± 0.008	0.025	i

Available Experimental Techniques for detecting 0νββ – decay.

Source = detector

Semiconductors

Heidelberg-Moscow, IGEX, COBRA, GERDA, MAJORANA

Cryogenic bolometers

CUORICINO, CUORE

Scintillators

SNO+, CANDLES, MOON, GSO, XMASS

Source ≠ detector

Time projection chambers (TPC)

NEMO-3, SuperNEMO, DCBA, EXO, NEXT

Formidable radioactivity background for Q<3MeV. For Cosmic Rays → underground (e.g. GRAN SASSO, Italy)

Current and Future Experiments

(K Zuber, Acta Phys. Pol.B 37 (2006) 1905 ;H Ejiri, J. Phys. Soc. Japan 74 (2005)20012)

Experiment	Isotope	Experimental approach	
CANDLES	48Ca	Several tons of CaF_2 crystals in Liquid scintillator	
CARVEL	^{48}Ca	100 kg $^{48}CaWO_4$ crystal scintillators	
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors	
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers	running as CUORICINO
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers	
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)	
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, expand to larger masses	
GSO	^{160}Gd	2t Gd_2SiO_3:Ce crystal scintillator in liquid scintillator	
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses	
MOON	^{100}Mo	several tons of Mo sheets between scint.	
SNO+	^{150}Nd	1000 t of Nd-loaded liquid scint.	
SuperNEMO	^{82}Se	100 kg of Se foils between TPCs	running as NEMO-3
Xe	^{136}Xe	1.56 t of Xe in liquid scint.	
XMASS	^{136}Xe	10 t of liquid Xe	

Geographic Distribution of Experiments

0νββ–decay: Exotic, it violates lepton number conservation. Not yet observed.

Table 1: Limits on neutrino-less $\beta^-\beta^-$ decays. $Q_{\beta\beta}$: Q value for the $0^+ \rightarrow 0^+$ ground state transition. $G^{0\nu}$: kinematical factor (phase space volume) in units of 10^{-14} y^{-1}, $T^{0\nu}_{1/2}$: half life in units of 10^{24} y and $\langle m_\nu \rangle$: the effective ν mass* in units of eV.

isotope	$A\%$	$Q_{\beta\beta}$ MeV	$G^{0\nu}$	$T^{0\nu}_{1/2}$ 10^{24}	$\langle m_\nu \rangle$ eV	Future experiments
^{48}Ca	0.187	4.276	4.46	> 0.014 a	< 7.2 - 45	CANDLES
^{76}Ge	7.8	2.039	0.44	> 19 b	< 0.22 - 0.41	GERDA
^{76}Ge	7.8	2.039	0.44	22 c	< 0.21 - 0.38	-
^{76}Ge	7.8	2.039	0.44	> 16 d	< 0.24 - 0.44	MAJORANA
^{82}Se	9.2	2.992	1.89	> 0.36 e	< 0.94 - 1.7	S-NEMO MOON
^{100}Mo	9.6	3.034	3.17	> 1.1 f	< 0.47 - 0.96	MOON AMoRE
^{116}Cd	7.5	2.804	3.24	> 0.17 g	< 1.5 - 2.8	COBRA $CdWO_4$
^{130}Te	34.5	2.529	2.86	> 2.8 h	< 0.35 - 0.59	CUORE
^{136}Xe	8.9	2.467	3.03	> 1.2 i	< 1.1 - 2.9	EXO KamLAND-Zen
^{150}Nd	5.6	3.368	13.4	> 0.018 j	< 1.7 - 2.4	S-NEMO SNO+ DCBA

Step 1: the transition operator as a product of two nuclear currents

$$\Omega = \tau_+ \tau_+ (-h_F + h_{GT}\, \sigma_{12} - h_T S_{12}), \tag{92}$$

where the three terms correspond to Fermi (F) , Gamow-Teller (GT) and Tensor (T) with

$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{q} \vec{\sigma}_2 \cdot \hat{q}) - \sigma_{12}, \quad \sigma_{12} = \vec{\sigma}_1 \cdot \vec{\sigma}_2. \tag{93}$$

One finds that

$$h_F = g_V^2(\vec{q}\,^2),$$
$$h_{GT}(\vec{q}\,^2) = g_A^2(\vec{q}\,^2)\left[1 - \frac{2}{3}\frac{\vec{q}\,^2}{\vec{q}\,^2 + m_\pi^2} + \frac{1}{3}\left(\frac{\vec{q}\,^2}{\vec{q}\,^2 + m_\pi^2}\right)^2 \right] + \frac{2}{3}\frac{g_M^2(\vec{q}\,^2)\vec{q}\,^2}{4m_p^2},$$
$$h_T(\vec{q}\,^2) = g_A^2(\vec{q}\,^2)\left[\frac{2}{3}\frac{\vec{q}\,^2}{\vec{q}\,^2 + m_\pi^2} - \frac{1}{3}\left(\frac{\vec{q}\,^2}{\vec{q}\,^2 + m_\pi^2}\right)^2 \right] + \frac{1}{3}\frac{g_M^2(\vec{q}\,^2)\vec{q}\,^2}{4m_p^2}. \tag{94}$$

In coordinate space one gets the potentials

$$V_x^{F/GT}(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty j_0(qr)\,\frac{h_x^{F/GT}(q)}{(q+\mu)}q\,dq,$$

$$V_x^T(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty -j_2(qr)\,\frac{h_x^T(q)}{(q+\mu)}q\,dq, \qquad (9)$$

where $j_n(x)$ are the spherical Bessel functions, r is the distance between nucleons and R, which makes the result dimensionless, is taken as $R = r_0 A^{1/3}$, with $r_0 = 1.2$ fm.

They are approximately Coulombic, since the intermediate Majorana neutrino is almost massless

The inclusion of form factor reduces the $|M^{0\nu\beta\beta}|^2$ by 30%

Step2: The role of short range correlations

$$< 0_i^+|V(r)|0_f^+ >_{SRC} = < 0_i^+|f(r)V(r)f(r)|0_f^+ > \qquad (0.2)$$

with

- f(r) The Jastrow correlation function:

  $$f(r) = 1 - Exp^{-ar^2}(1 - br^2), a = 1.1 \mathrm{f}m^{-2}, b = 0.68 \mathrm{f}m^{-2} \qquad (0.3)$$

  It suppresses the nuclear ME roughly 15-25 %

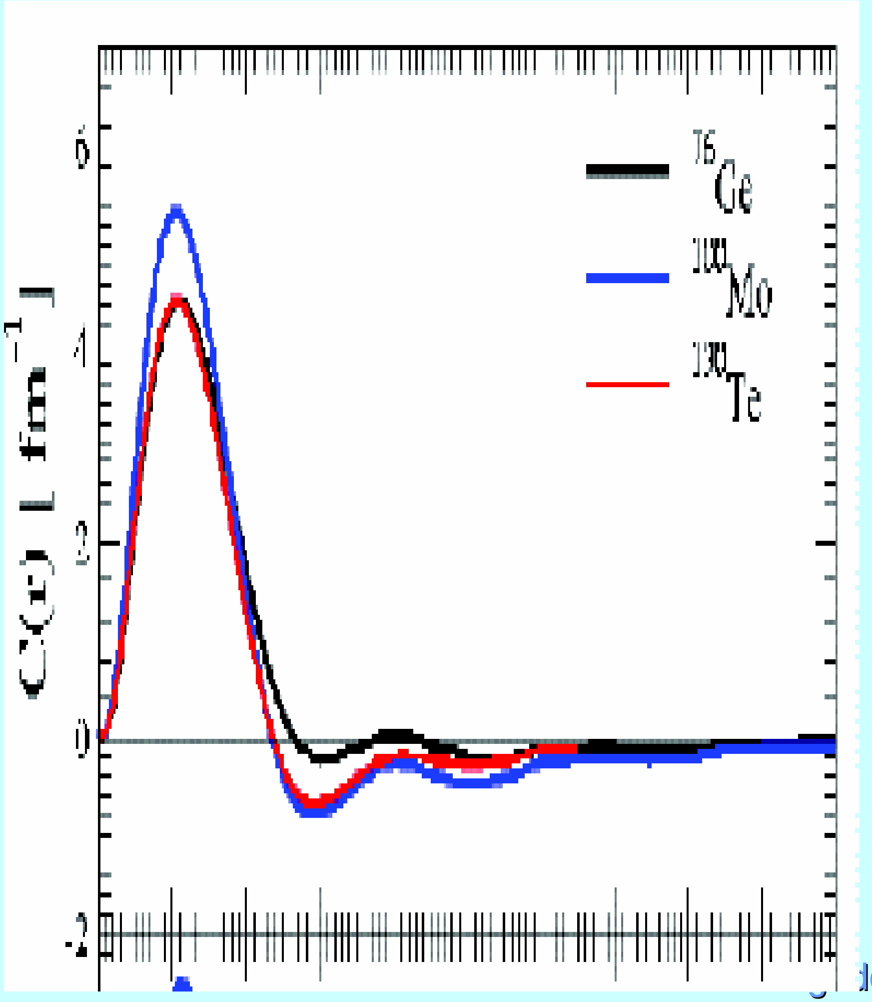
- Unitary Correlation Operator Method (UCOM)(Simkovic, Faessler, Muther, Rodin & Stauf (2009)

$$\Phi_J \longrightarrow \Psi_J = C_r \Phi_J$$

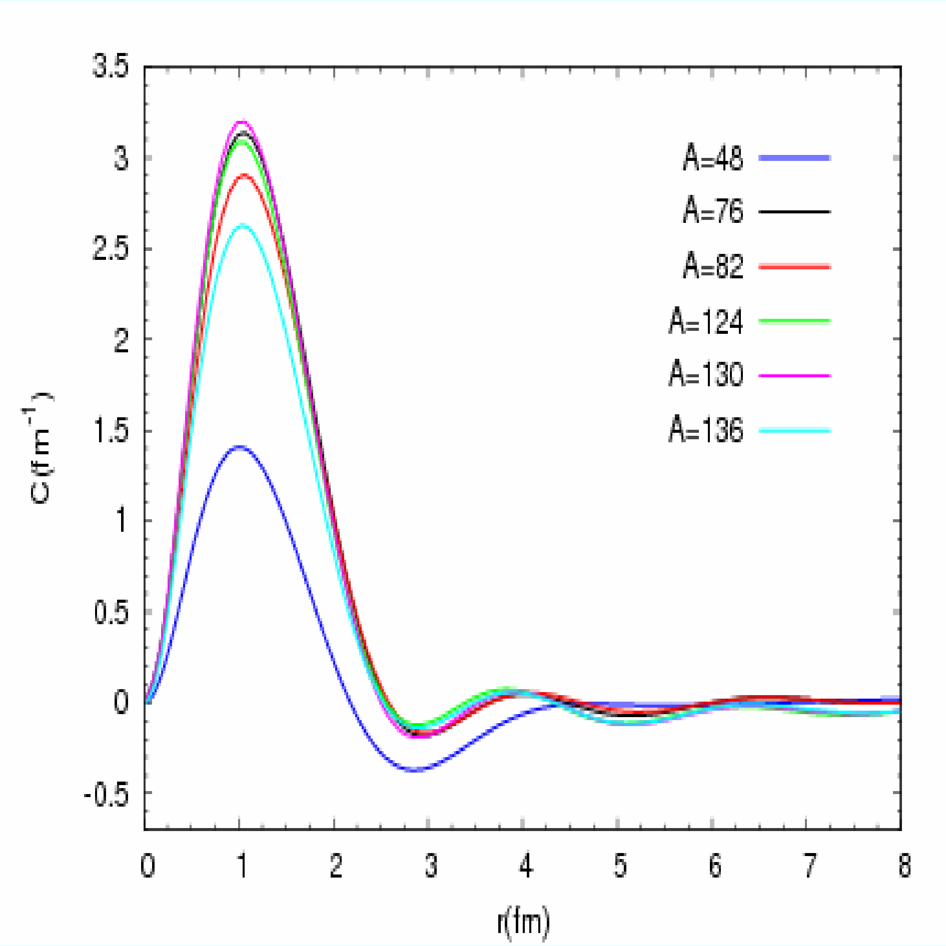
The form of UCOM is complicated (it must be given for each L-S; it will not be discussed here)
It suppresses the nuclear ME less (around 5 %)

Short Range Correlations (SRC)

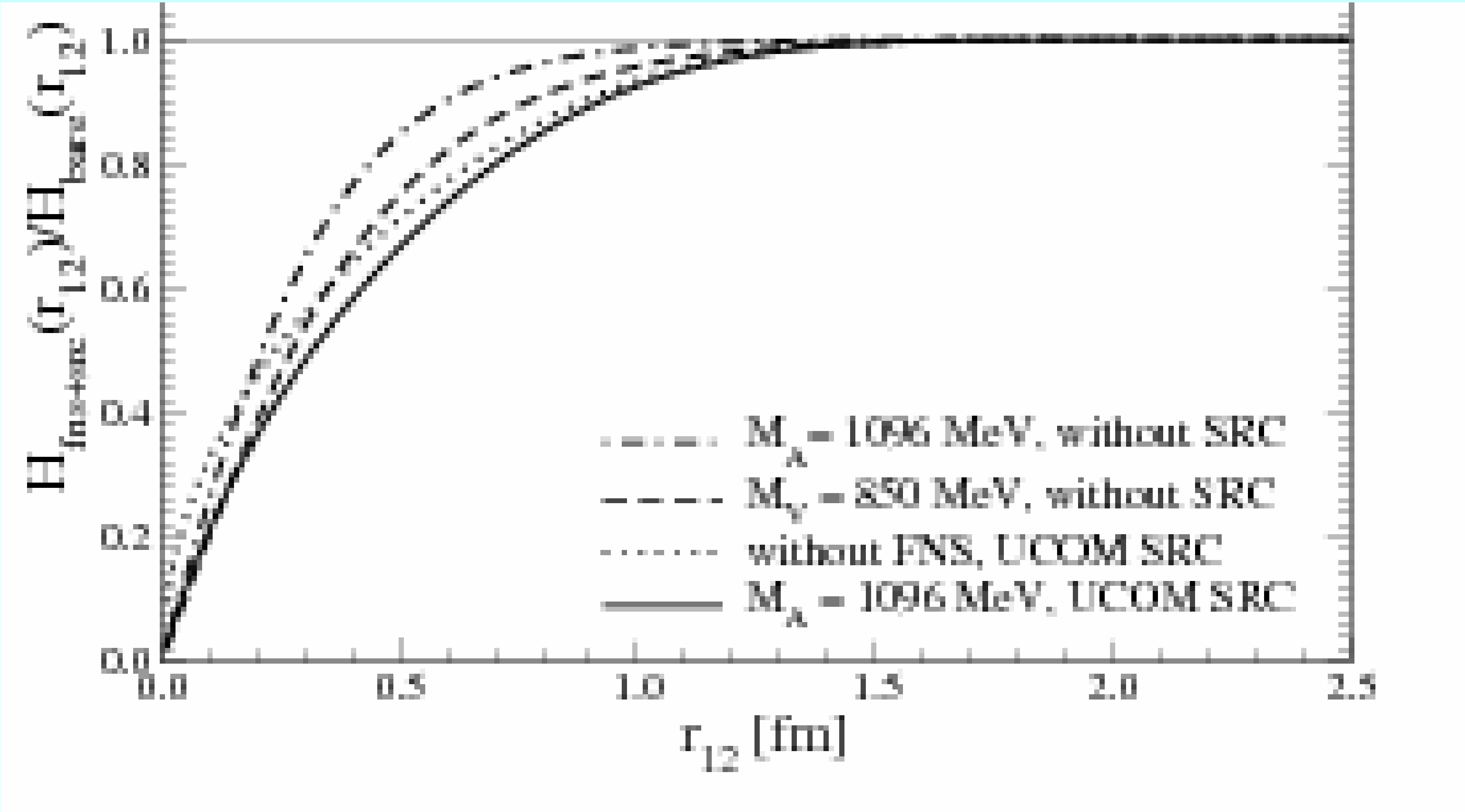
Tuebingen Group



Menendez , Poves, Caurier & Nowachi



SRC and FNS (finite nucleon Size) for A=76 (Tuebingen Group)



Step 3: b) The Quasi Particle Random Phase Approximation (QRPA)

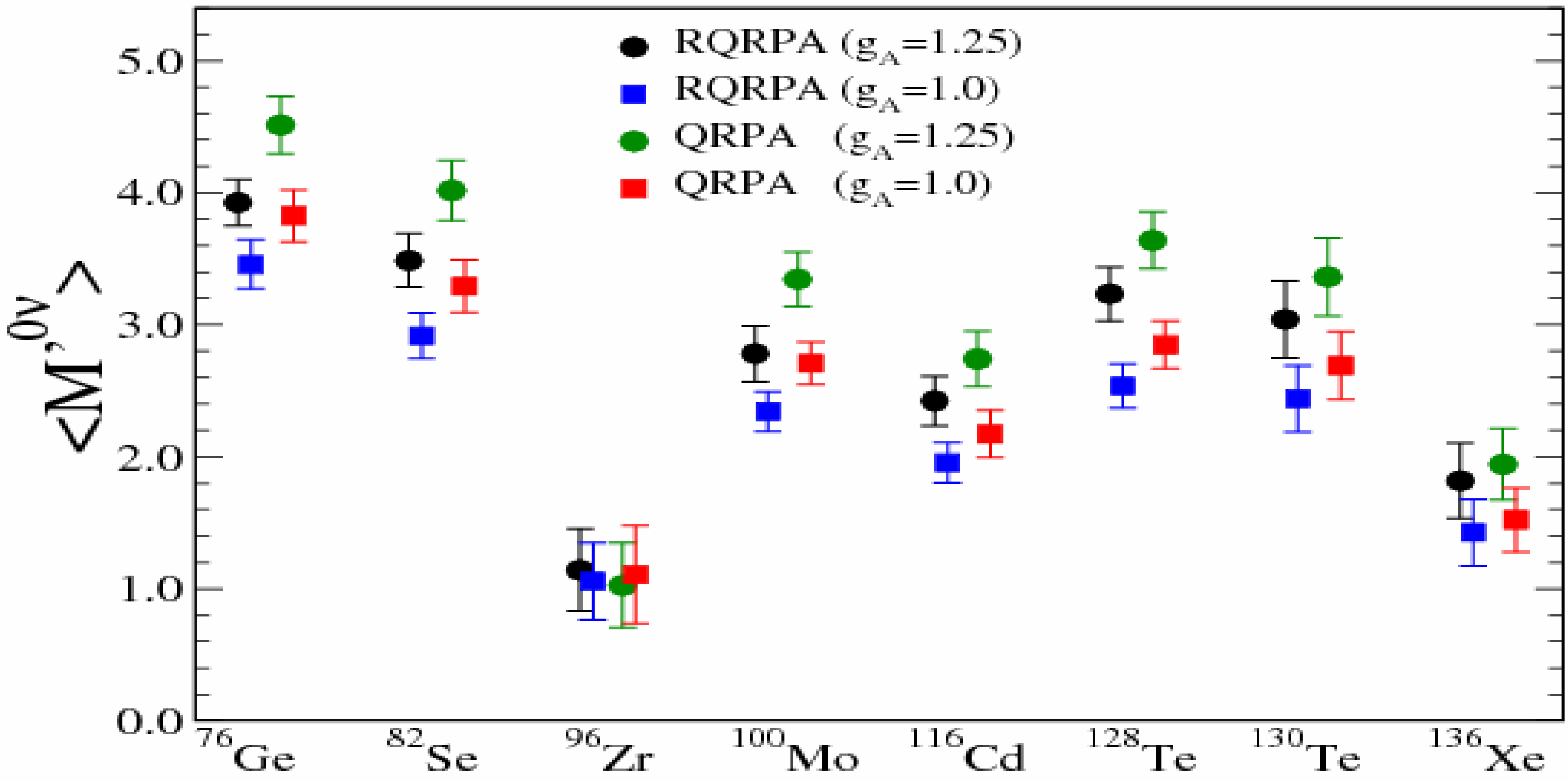
- Unlimited number of single particle states (in practice around 20)
- Very limited number of configurations (only 2 quasiparticles)
- An effective interaction as in ISM but with the additional three global parameters:

-g_{pair}: multiplying the pairing part of the interaction, for both protons and neutrons (Standard in BCS approach)

-g_{ph}: Multiplying the particle hole block

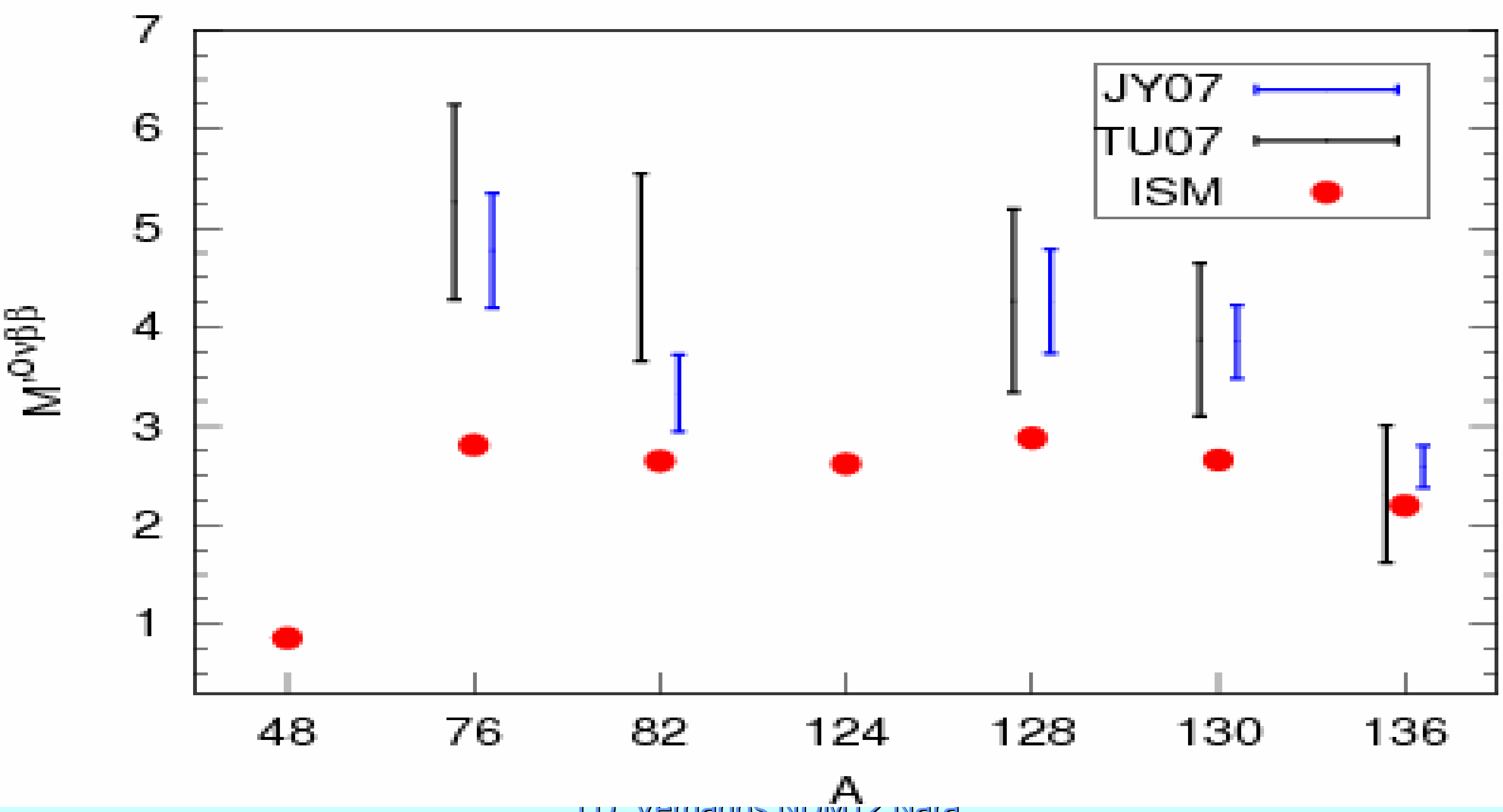
-g_{pp}: Multiplying the particle -particle block

The Tuebingen07 ME including the uncertainty from Experimental 2ν



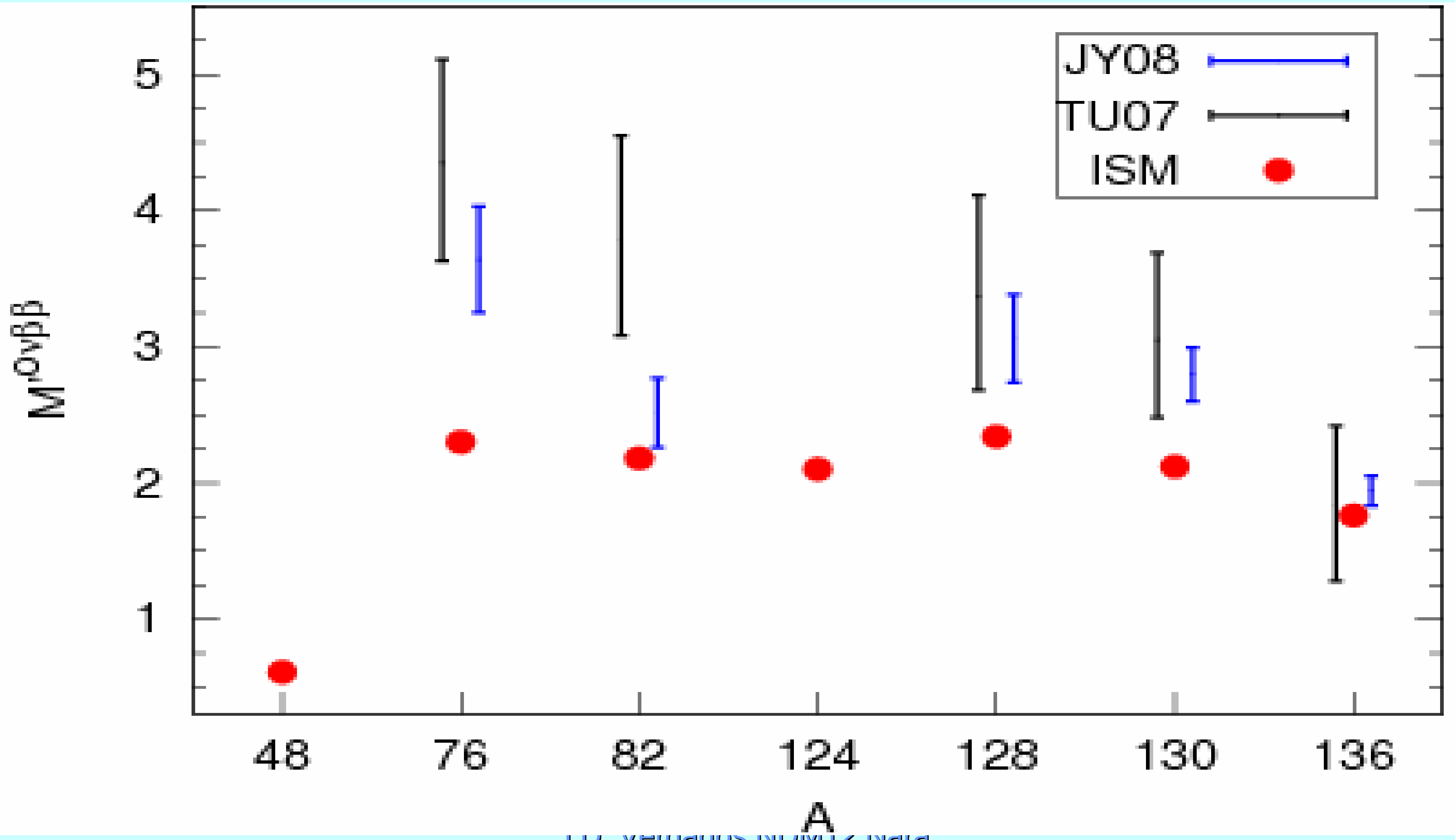
The Matrix elements with UCOM SRC

TU07: Rodin, Faessler, Simkovic&Vogel; JY07:Suhonen&Kortelinen



The Matrix elements with Jastrow SRC

TU07: Rodin, Faessler, Simkovic&Vogel; JY07:Suhonen&Kortelinen



Step 3: a) The Interacting Shell Model: Diagonalize huge matrices

The ISM Model Space

- For ^{48}Ca:
  the entire pf shell:
  $$0f_{7/2}, 1p_{3/2}, 0f_{5/2}, 1p_{1/2}$$
  Interaction employed: KB3
- for ^{76}Ge and ^{82}Se:
  $$1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{7/2}$$
  Interaction used:GCN28.50
- for ^{124}Sn,^{128}Te,^{130}Te,^{136}Xe:
  $$0g_{7/2}, 1d_{3/2}, 1d_{5/2}, 2s_{1/2}, 0h11/2$$
  Interaction used:GCN50.82

Step 3: a) The Interacting Shell Model:

$0\nu\beta\beta$ Transition	$M_{no\,SRC}$	$M^{0\nu\beta\beta}_{UCOM}$	$M^{0\nu\beta\beta}_{Jastrow}$	$\Delta M_{UCOM}(\%)$	$\Delta M_{Jastrow}(\%)$
$^{48}Ca \rightarrow {}^{48}Ti$	0.92	0.85	0.61	8	34
$^{76}Ge \rightarrow {}^{76}Se$	2.96	2.81	2.30	5	22
$^{82}Se \rightarrow {}^{82}Kr$	2.79	2.64	2.18	5	22
$^{124}Sn \rightarrow {}^{124}Te$	2.77	2.62	2.10	5	24
$^{128}Te \rightarrow {}^{128}Xe$	3.05	2.88	2.34	6	23
$^{130}Te \rightarrow {}^{130}Xe$	2.81	2.65	2.12	6	25
$^{136}Xe \rightarrow {}^{136}Ba$	2.32	2.19	1.76	6	24

A powerful problem solver

Once all mighty god gave five golden cows made of pure gold to be divided as follows:

- The LBSM theorists should get 1/3
- The RPA guys should also get 1/3 and
- The IBM people only 1/6

Condition: no cow should be carved.
Since hey did no know how to execute God's will, they went, where else?, to Mullah Nazrudin. He thought for a wile and ordered his wife to bring in their own cow, which he naturally valued as golden.
Now there six cows in the pack. Naturally the LBSM and the RPA got two each and the IBM got one. The Mullah's cow was left and his wife took it back to the stable.

Was it a fair deal?

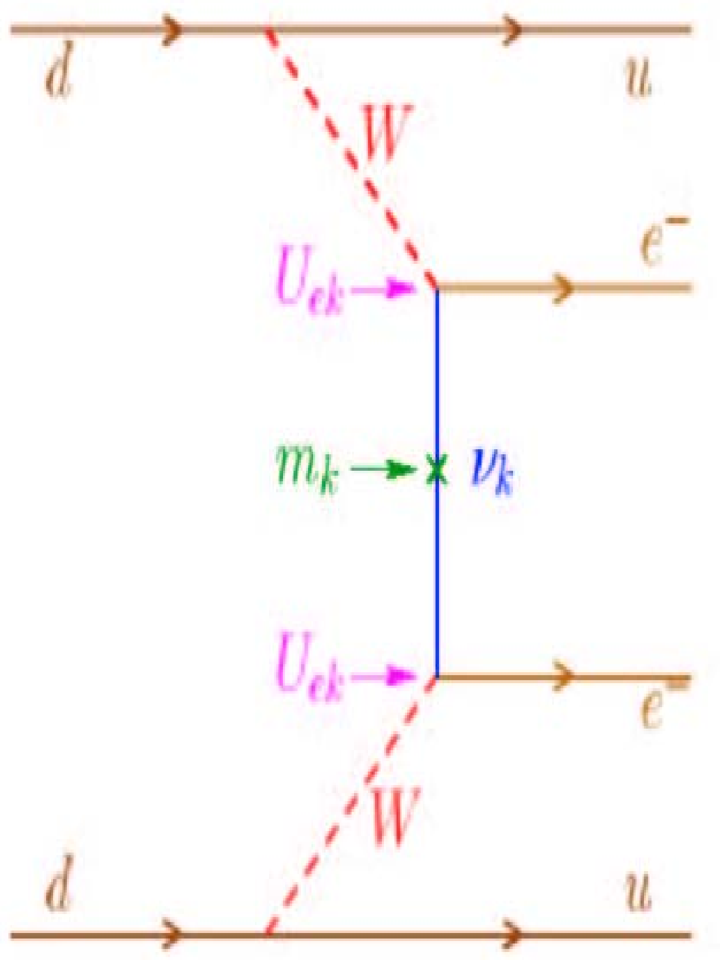
- Mullah did not know how to sum infinite series, but

$$\frac{5}{3}+\frac{1}{3}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{3}+\frac{1}{3}=2$$

$$\frac{5}{6}+\frac{1}{6}5\left(\frac{1}{6}+\frac{1}{6^2}+\frac{1}{6^3}\cdots\right)=\frac{5}{6}+\frac{1}{6}=1$$

Diagrammatic Representation of 0ν-ββ decay (mass term only)

Quark Level



Nuclear Level

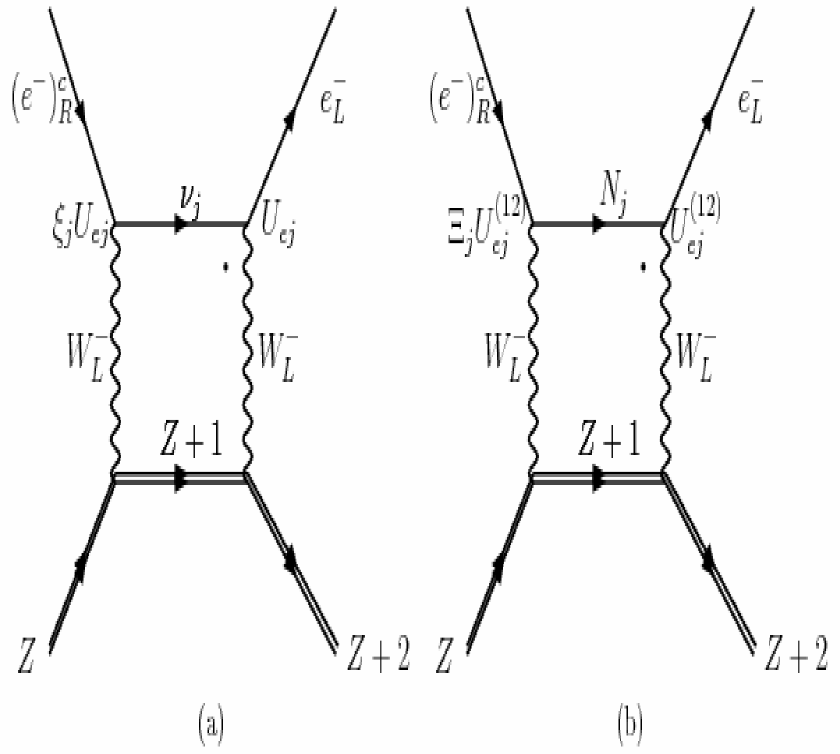


Figure 5: The neutrino mass contribution at the nuclear level in the presence of left handed currents for light intermediate neutrino (a) and heavy neutrino (b).

Effective neutrino mass $\langle m_\nu \rangle$ encountered in 0ν ββ-decay

[$\alpha=\alpha_2-\alpha_1$, $\beta=\alpha_3-\alpha_1+2\delta_{13}$,

α_1 , α_2 , α_3 Majorana phases]

Mass scale: m_1 (normal); m_3 (inverted)

$$\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

Measure the sum of the energies of the two electrons. 0ν ββ is a discreet line at the end point. 2ν ββ has a continuous spectrum. A need for good energy resolution.