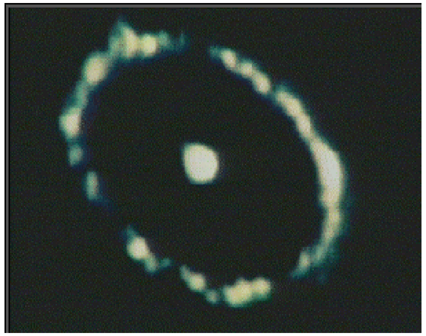
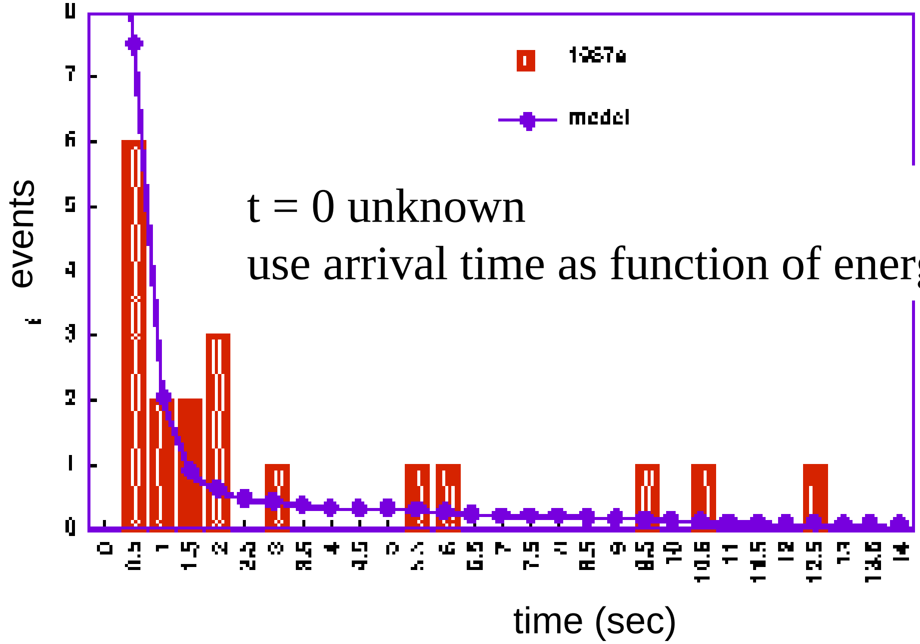
Neutrino Mass from Time-of-flight

Supernova 1987a in Large Magellenic Cloud
L = 50 kpc (150 light years)



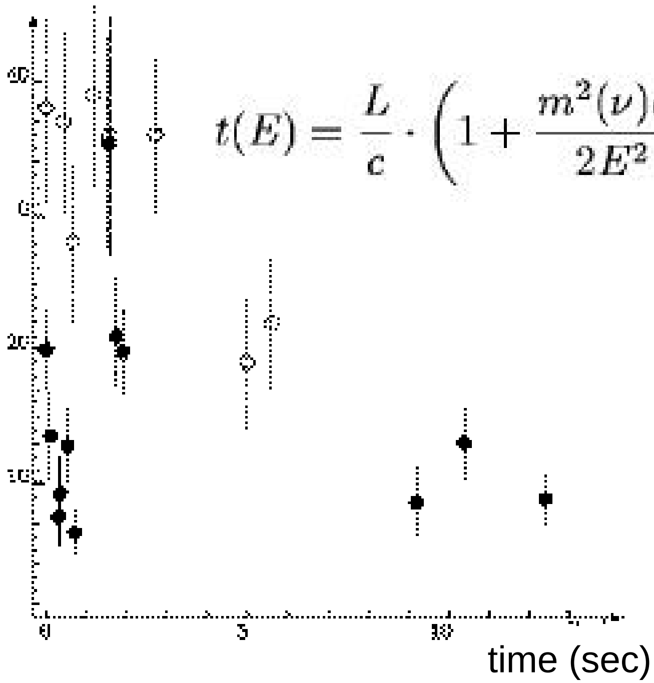
$$p + e^- \rightarrow n + \nu_e$$

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_{e}, \; \nu_\mu + \bar{\nu}_\mu$$



t = 0 unknown

use arrival time as function of energy ⟹



$$t(E) = \frac{L}{c} \cdot \left(1 + \frac{m^2(\nu)c^4}{2E^2}\right)$$

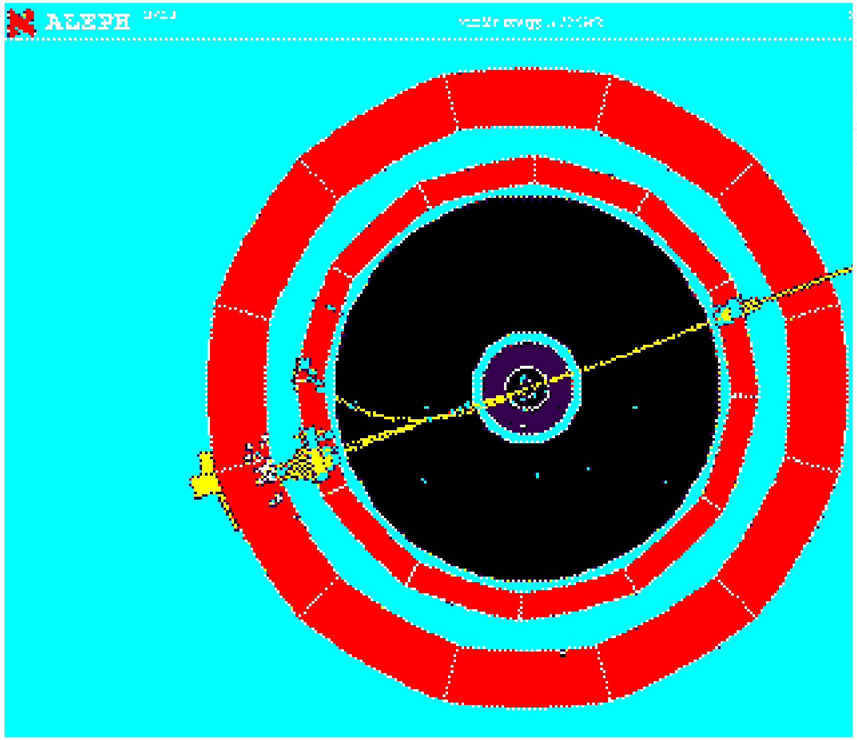
$$M(\nu_e) < 23 \text{ eV}/c^2$$

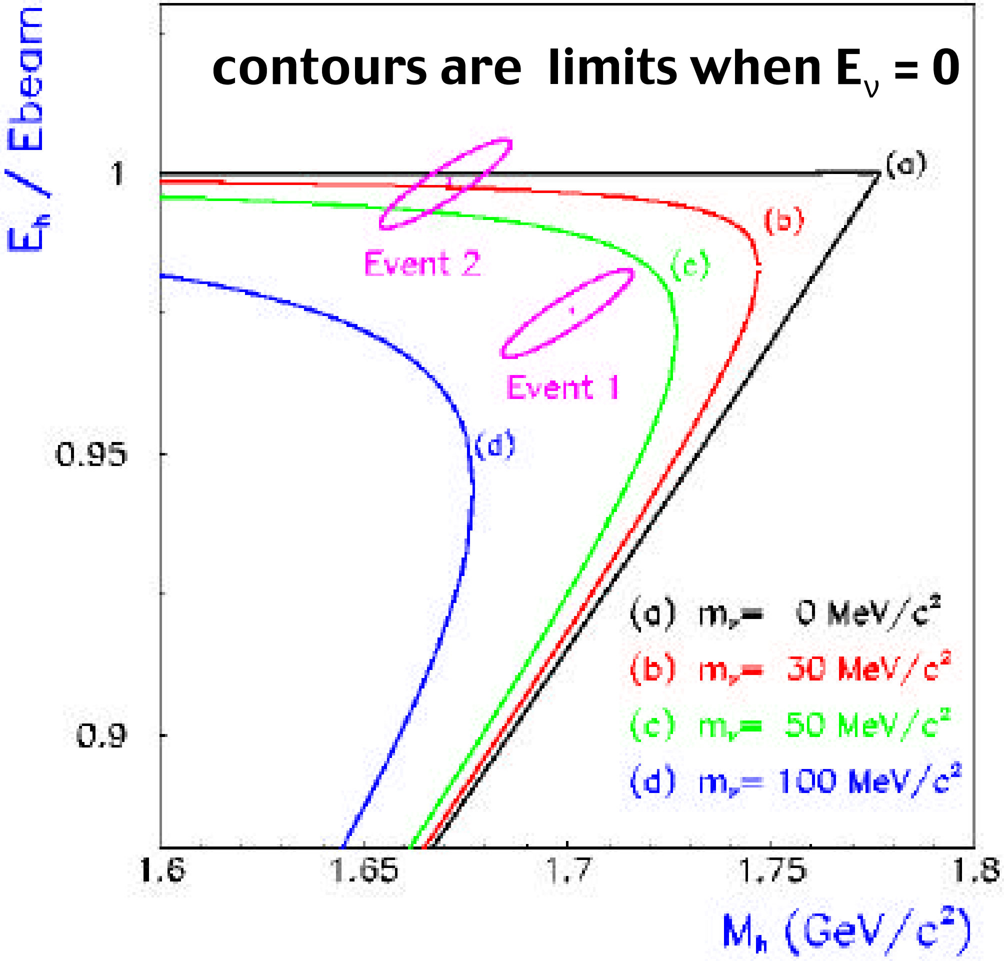
Limits on $M(\nu_\tau)$

Measured in τ decays at LEP

$e^+e^- \rightarrow \tau^+\tau^-$

$\tau \rightarrow n\pi\nu_\tau$ (n=3, 5, 6)





Limits on $M(\nu_\tau)$

In tau rest frame energy of hadronic system h:

$$E^*_h = \frac{m_\tau^2 + m_h^2 - m_\nu^2}{2\, m_\tau}$$

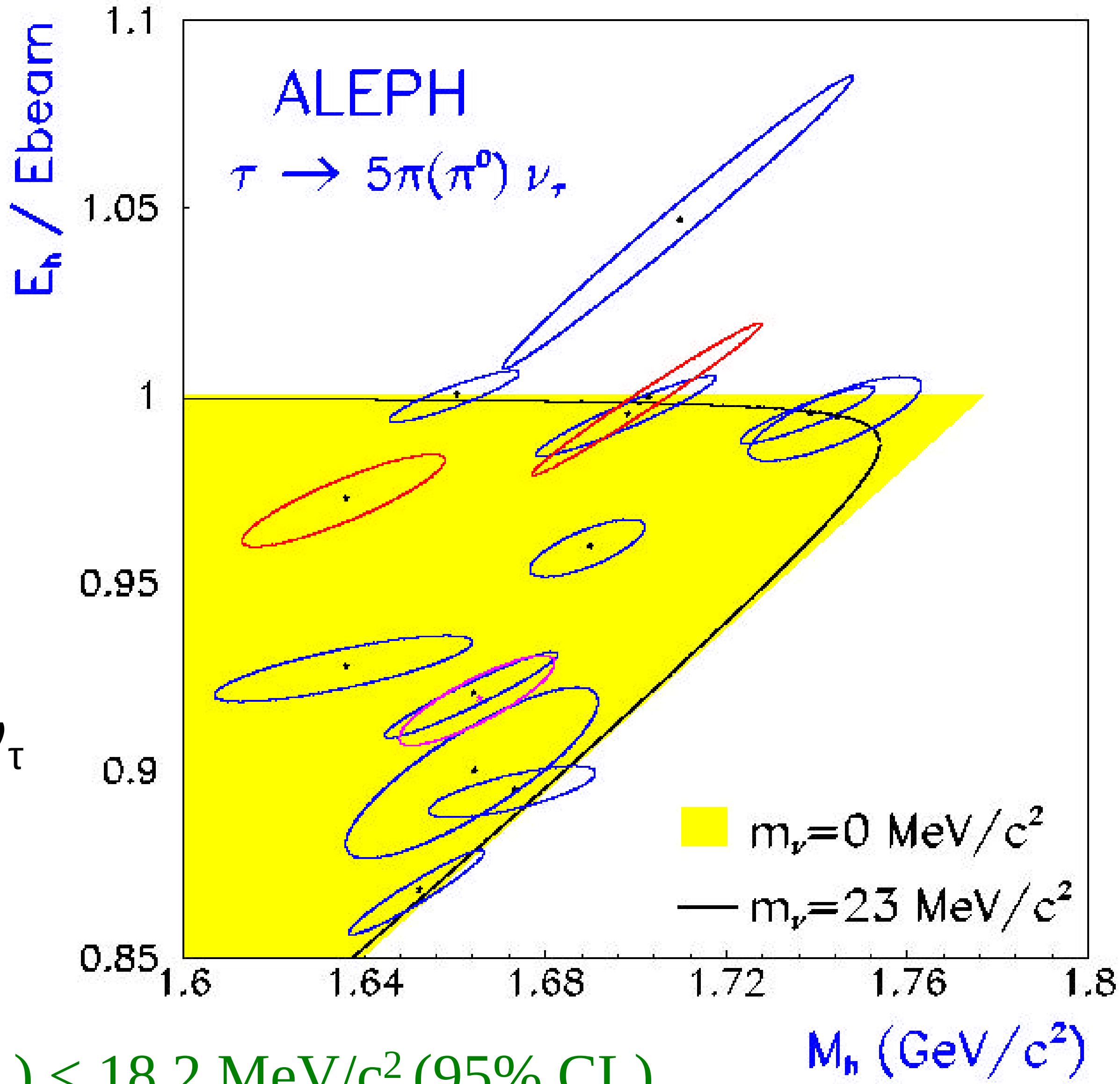
Total decays

2939 : $\tau^- \rightarrow 2\,\pi^- \pi^+ \nu_\tau$

52 : $\tau^- \rightarrow 3\,\pi^- 2\pi^+ \nu_\tau$

3 : $\tau^- \rightarrow 3\,\pi^- 2\pi^+ \pi^0 \nu_\tau$

only events with high m_h contribute to $M(\nu_\tau)$ limit

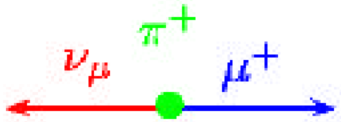


$M(\nu_\tau) < 18.2$ MeV/c^2 (95% CL)

Limits on M(ν_μ)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ (Two body decay)

Decay at rest:



$$|\vec{p}_\nu| = |\vec{p}_\mu|$$

$$m_\pi = E_\nu + E_\mu$$

$$\rightarrow m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 \cdot m_\pi \cdot \sqrt{m_\mu^2 + p_\mu^2}$$

Pionic atoms:	$m_\pi = 139.570180(350)$ MeV
Myonium:	$m_\mu = 105.658357(5)$ MeV
Magnetic spektrometer (PSI):	$p_\mu = 29.791998(110)$ MeV

M(ν_μ) < 170 keV/c^2 (95% CL)

Limits on $M(\nu_e)$

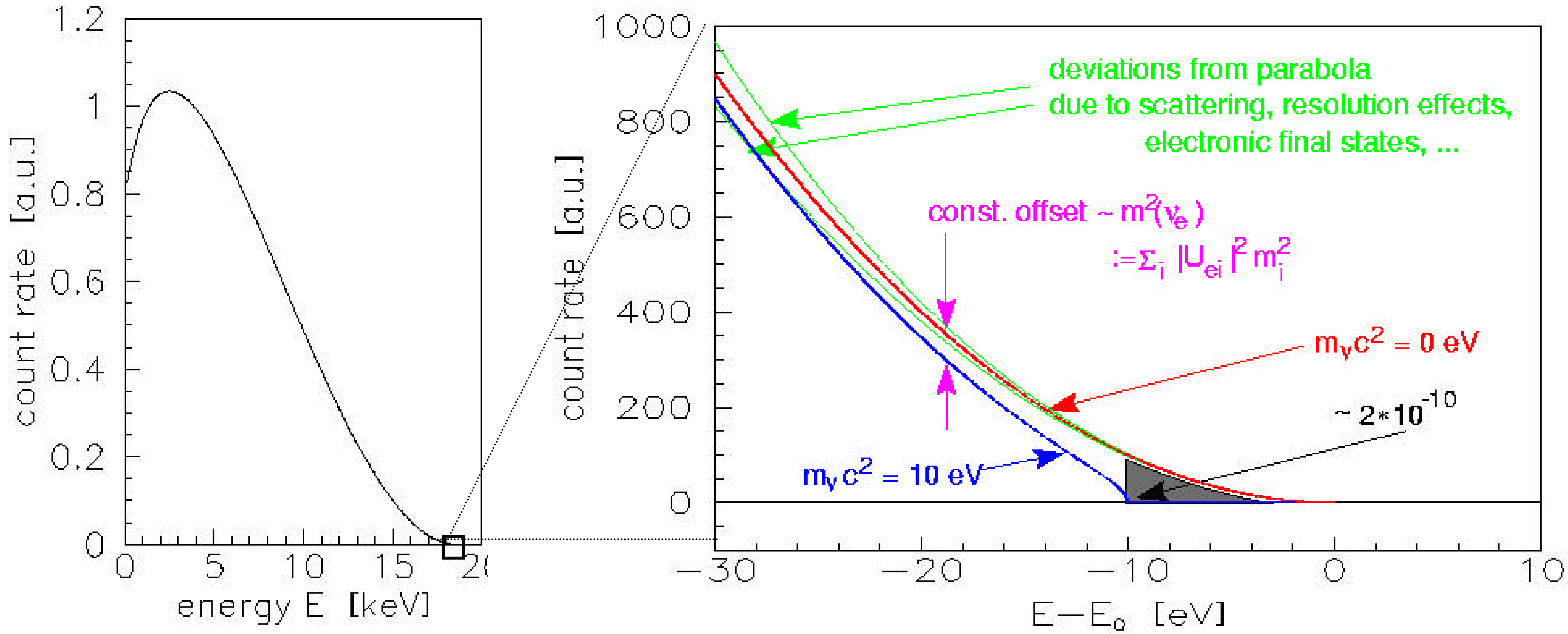
Tritium β decay:

$^3\mathrm{H} \longrightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$:

superallowed

E_0 = 18.6 keV

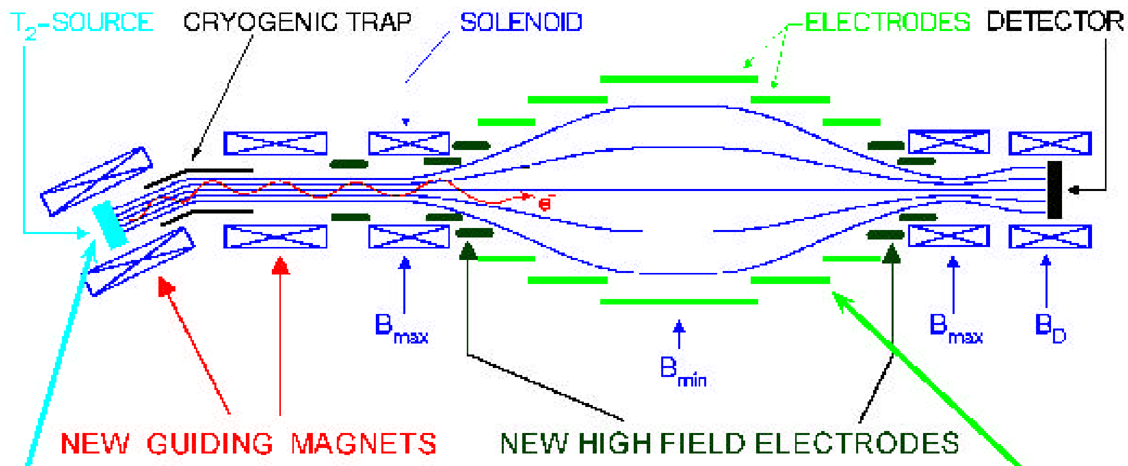
$t_{1/2}$: 12.3 a

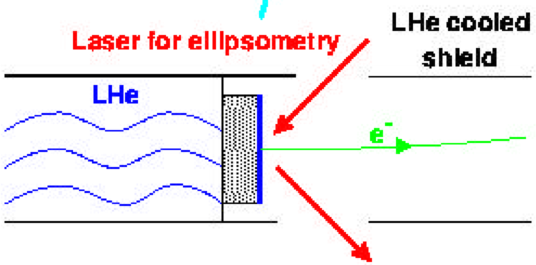


Detailed study of end-point of spectrum: many experiments

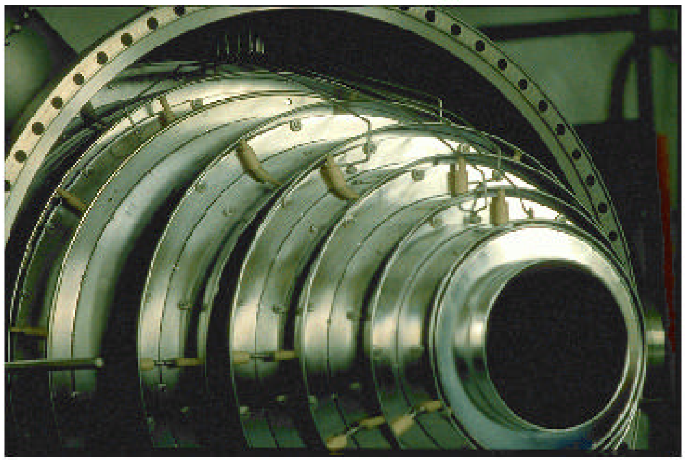
Limits on $M(\nu_e)$

Mainz spectrometer





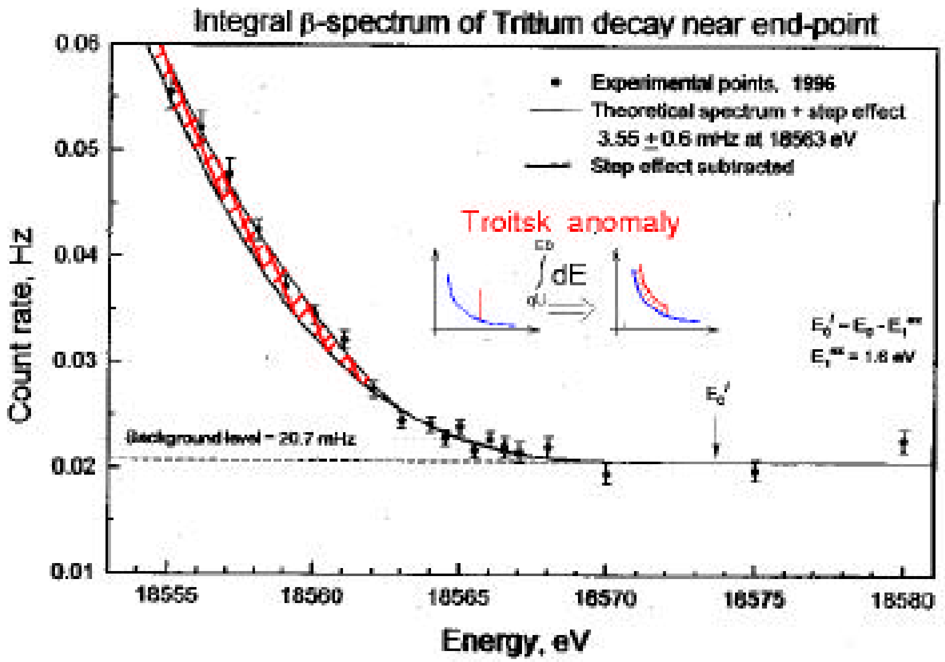
- T_2 film at 1.86 K
- quench condensed on graphite substrate (HOPG)
- $\approx$ 450 Å thick, area 2 cm^2
- thickness measured. by ellipsometry



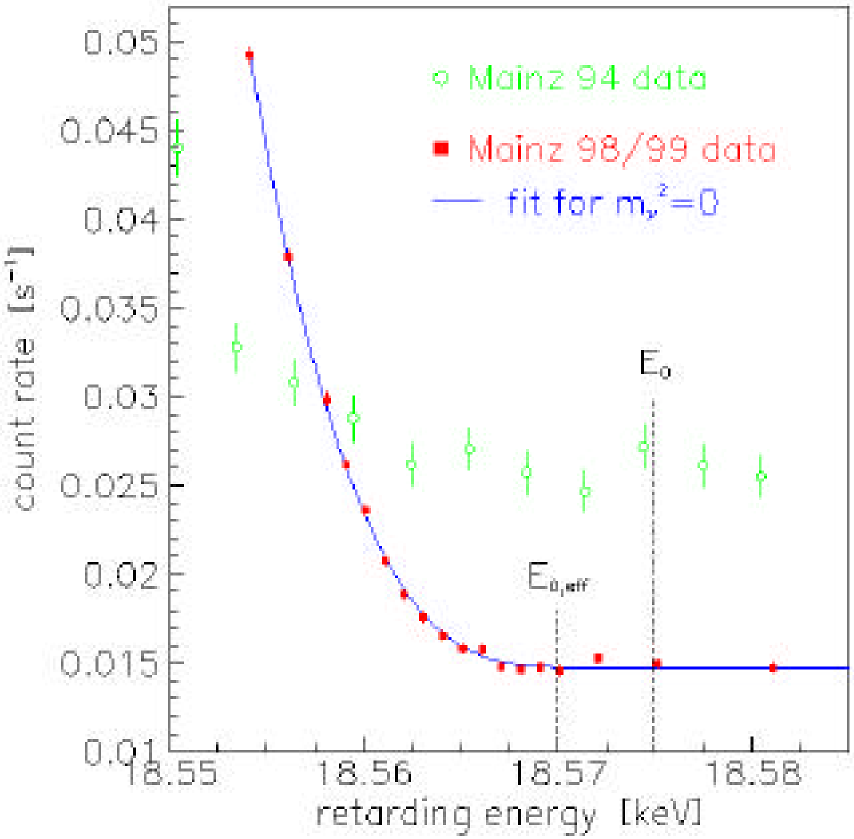
Limits on M(ν_e)

End-point spectra

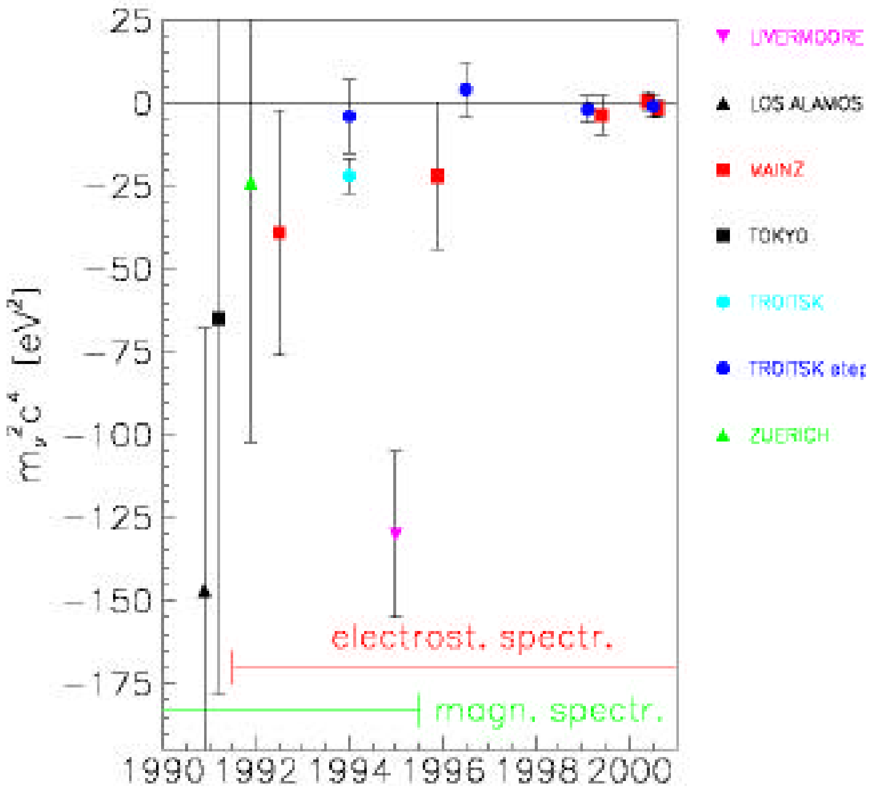
Troitsk experiment



Mainz experiment



Limits on $M(\nu_e)$

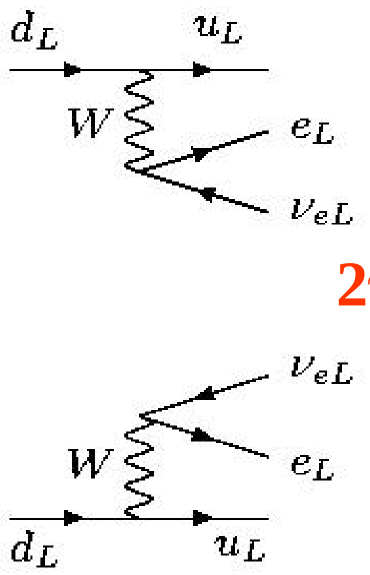


Experiment	measured mass squared	formal limit	C.L.	Year
Mainz	−1.6 ± 2.5 ± 2.1	2.2	95 %	2000
Troitsk	−1.0 ± 3.0 ± 2.1 (**)	2.5	95 %	2000
Zürich	−24 ± 48 ± 61	11.7	95 %	1992
Tokyo INS	− 65 ± 85 ± 65	13.1	95%	1991
Los Alamos	− 147 ± 68 ± 41	9.3	95%	1991
Livermore	− 130 ± 20 ± 15	7.0	95%	1995
China	− 31 ± 75 ± 48	12.4	95%	1995
Average of PDG (98)	−27 ± 20	15	95 %	1998

Masses in units of eV.

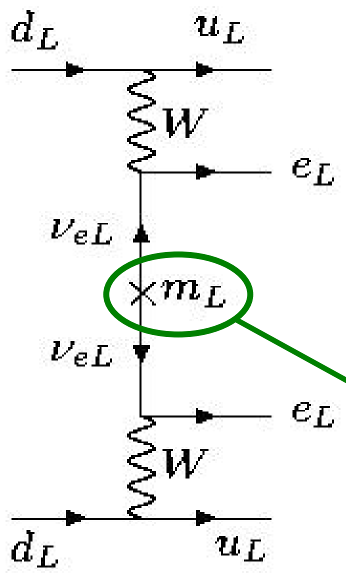
Double Beta Decay

A(Z,N) → A(Z+2, N−2)+2e$^-$+2ν_e



2νββ

A(Z,N) → A(Z+2, N−2)+2e$^-$

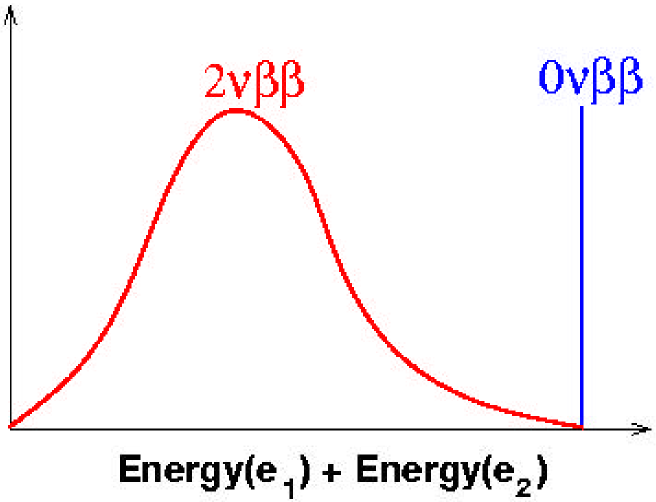


0νββ

(neutrino-less)

Only possible M(ν) ≠ 0

Majorana neutrino $\nu = \overline{\nu}$

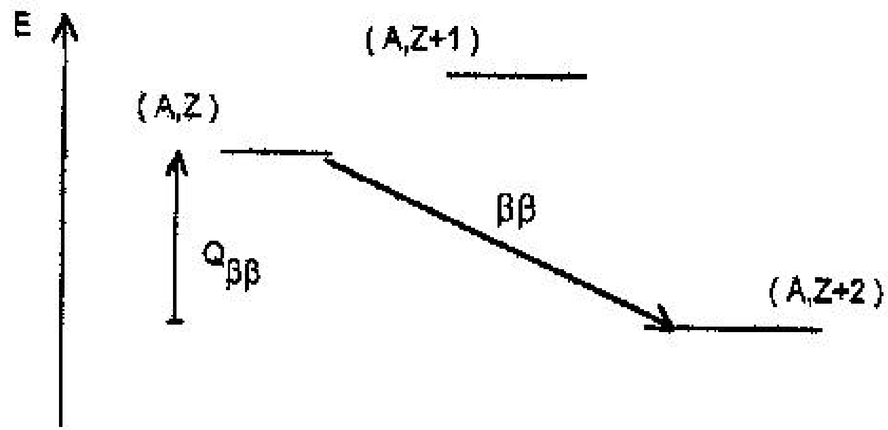


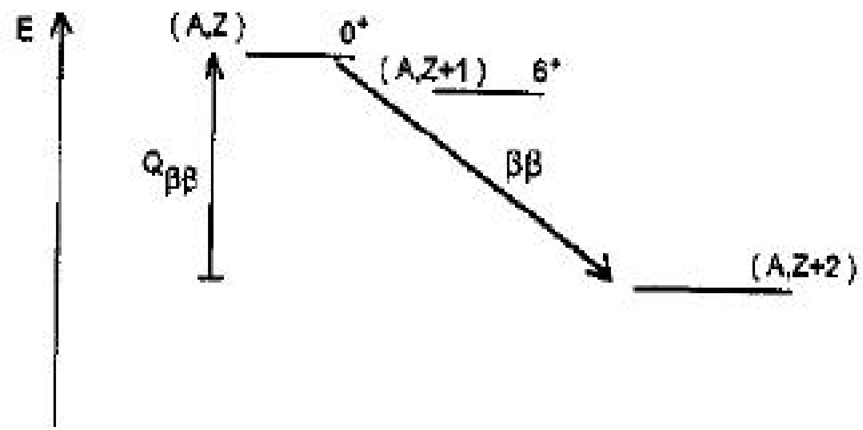
Only a few possible double beta isotopes

EMETTEURS β^-			
Transition	$Q_{2\beta}$ (keV)	Abondance (%)	Energie du niveau 2^+
$^{*48}Ca \longrightarrow {}^{48}Ti$	987 ± 4	0,0035	889
$^{*46}Ca \longrightarrow {}^{46}Ti$	4271 ± 4	0,187	984
$^{*70}Zn \longrightarrow {}^{70}Ge$	1001 ± 3	0,62	-
$^{*76}Ge \longrightarrow {}^{76}Se$	$2039,6 \pm 0,9$	7,8	559
$^{80}Se \longrightarrow {}^{80}Kr$	130 ± 9	49,87	-
$^{*82}Se \longrightarrow {}^{82}Kr$	2995 ± 6	9,2	776
$^{86}Kr \longrightarrow {}^{86}Sr$	1256 ± 5	17,3	1077
$^{*94}Zr \longrightarrow {}^{94}Mo$	$1145,3 \pm 2,5$	17,4	871
$^{*96}Zr \longrightarrow {}^{96}Mo$	3350 ± 3	2,8	778
$^{98}Mo \longrightarrow {}^{98}Ru$	112 ± 7	24,1	-
$^{*100}Mo \longrightarrow {}^{100}Ru$	3034 ± 6	9,6	540
$^{104}Ru \longrightarrow {}^{104}Pd$	1299 ± 4	18,7	556
$^{110}Pd \longrightarrow {}^{110}Cd$	2013 ± 19	11,8	658
$^{*114}Cd \longrightarrow {}^{114}Sn$	534 ± 4	28,7	-
$^{*116}Cd \longrightarrow {}^{116}Sn$	2802 ± 4	7,5	1294
$^{122}Sn \longrightarrow {}^{122}Te$	364 ± 4	4,56	-
$^{*124}Sn \longrightarrow {}^{124}Te$	$2288,1 \pm 1,6$	5,64	603
$^{*128}Te \longrightarrow {}^{128}Xe$	868 ± 4	31,7	443
$^{*130}Te \longrightarrow {}^{130}Xe$	2583 ± 4	34,7	536
$^{*134}Xe \longrightarrow {}^{134}Ba$	847 ± 10	10,4	605
$^{*136}Xe \longrightarrow {}^{136}Ba$	2479 ± 8	8,9	4819
$^{142}Ce \longrightarrow {}^{142}Nd$	$1417,6 \pm 2,5$	11,1	-
$^{146}Nd \longrightarrow {}^{146}Sm$	56 ± 5	17,2	-
$^{*148}Nd \longrightarrow {}^{148}Sm$	$1928,3 \pm 1,9$	5,7	559
$^{*150}Nd \longrightarrow {}^{150}Sm$	$3667,1 \pm 2,2$	5,6	334
$^{154}Sm \longrightarrow {}^{154}Gd$	$1251,9 \pm 1,5$	22,6	123
$^{160}Gd \longrightarrow {}^{160}Dy$	$1729,5 \pm 1,4$	21,8	87
$^{170}Er \longrightarrow {}^{170}Yd$	$653,9 \pm 1,6$	14,9	84
$^{176}Yb \longrightarrow {}^{176}Hf$	$1078,8 \pm 2,7$	12,6	86
$^{*186}W \longrightarrow {}^{186}Os$	$490,3 \pm 2,2$	28,6	137
$^{*192}Os \longrightarrow {}^{192}Pt$	417 ± 4	41,0	317
$^{*198}Pt \longrightarrow {}^{198}Hg$	1047 ± 4	7,2	412
$^{*204}Hg \longrightarrow {}^{204}Pb$	$416,5 \pm 1,9$	6,9	-
$^{232}Th \longrightarrow {}^{232}U$	856 ± 6	100	48
$^{*238}U \longrightarrow {}^{238}Pu$	$1145 \pm 1,7$	99,275	44
EMETTEURS β^+			
Transition	$Q_{2\beta}$ (keV)	Abondance (%)	Energie du niveau 2^+
$^{78}Kr \longrightarrow {}^{78}Se$	$833,1 \pm 8$	0,356	614
$^{96}Ru \longrightarrow {}^{96}Mo$	$677,1 \pm 8$	5,5	-
$^{*106}Cd \longrightarrow {}^{106}Pd$	$734,0 \pm 7,8$	1,25	512
$^{*124}Xe \longrightarrow {}^{124}Te$	$821,0 \pm 2,7$	0,096	603
$^{130}Ba \longrightarrow {}^{130}Xe$	$538,1 \pm 8$	0,106	-
$^{136}Ru \longrightarrow {}^{136}Ba$	$365,0 \pm 5,0$	0,190	-

Table 1 : Emetteurs potentiels $2\beta^-$ et $2\beta^+$. Les valeurs de $Q_{2\beta}$ sont extraites de Wapstra et Audi, *Nucl. Phys.* **A432** (1985)55   * Noyaux mesurés.

Must be energetically allowed and single beta decay suppressed





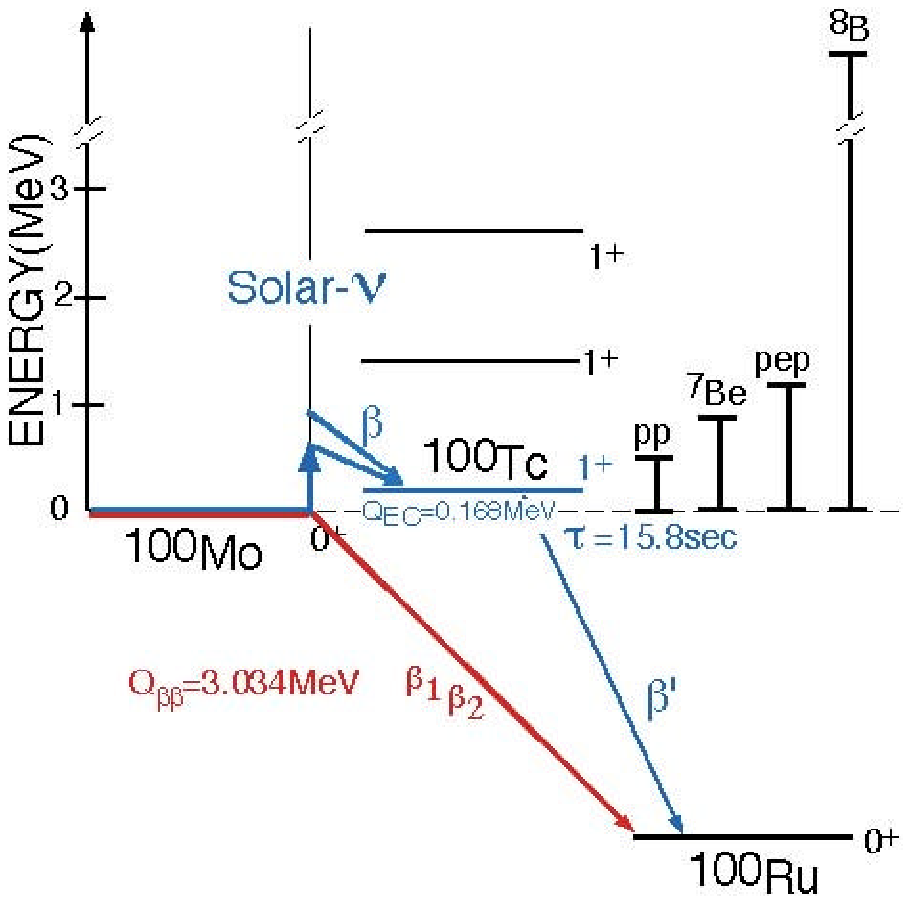
Example: ^{100}Mo in MOON detector

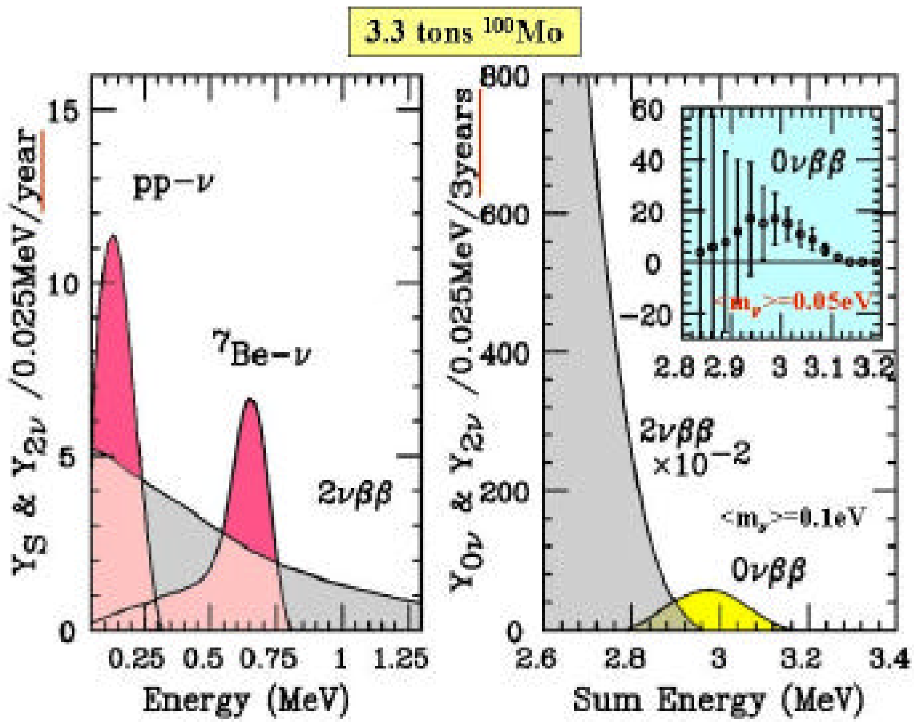
Mo(42,48) → Ru(44, 46)

Both:

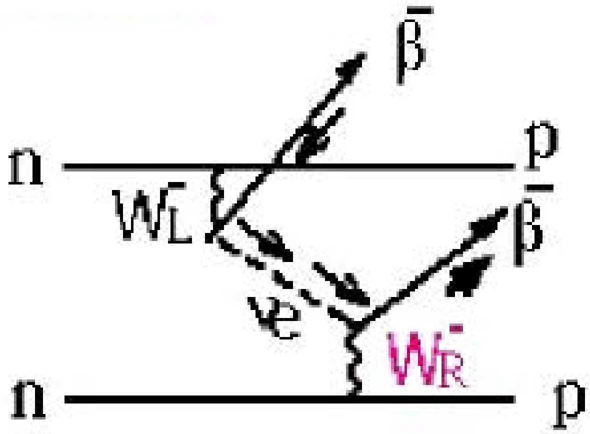
Double beta decay: $^{100}Mo \rightarrow {}^{100}Ru + 2e^{-} (+ 2\nu_e)$

Solar neutrino: $^{100}Mo + \nu_e \rightarrow {}^{100}Mo \rightarrow {}^{100}Tc + e^{-} \rightarrow {}^{100}Ru + e^{-}$

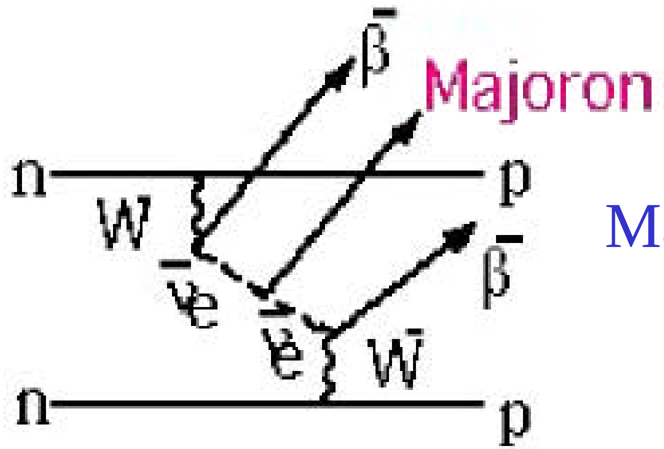




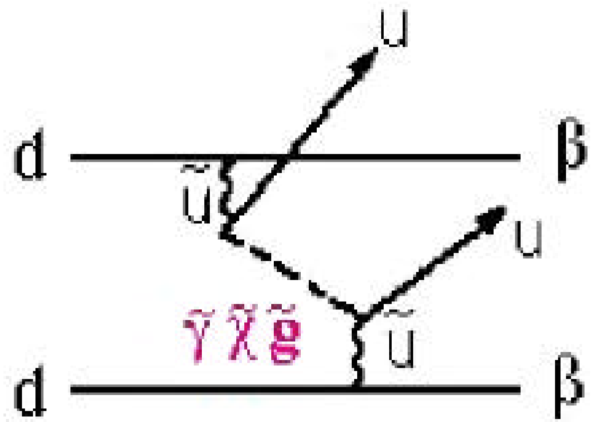
Physics beyond Standard Model in 0νββ



Right-Handed Currents



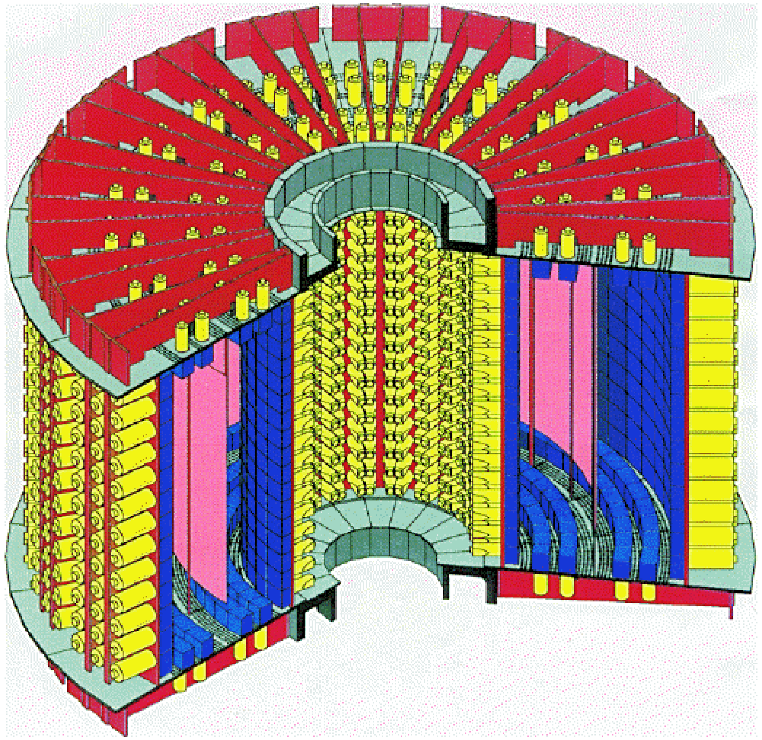
Majoron production

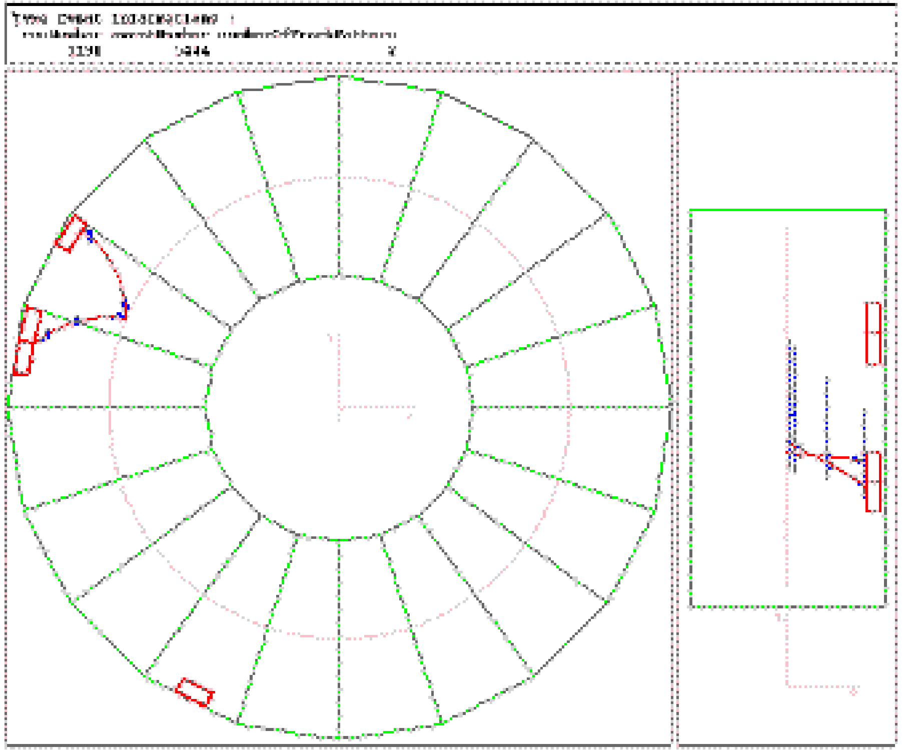


Supersymmetry

NEMO 3 (^{100}Mo)

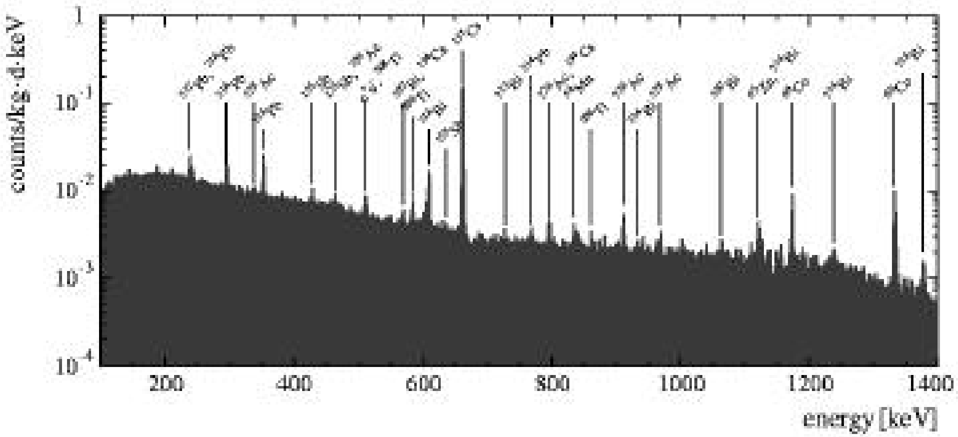
At Modane laboratory in Frejus tunnel

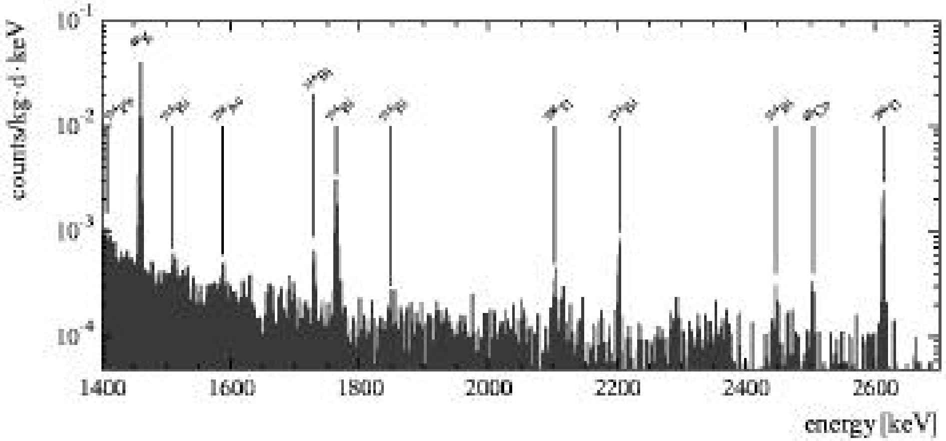


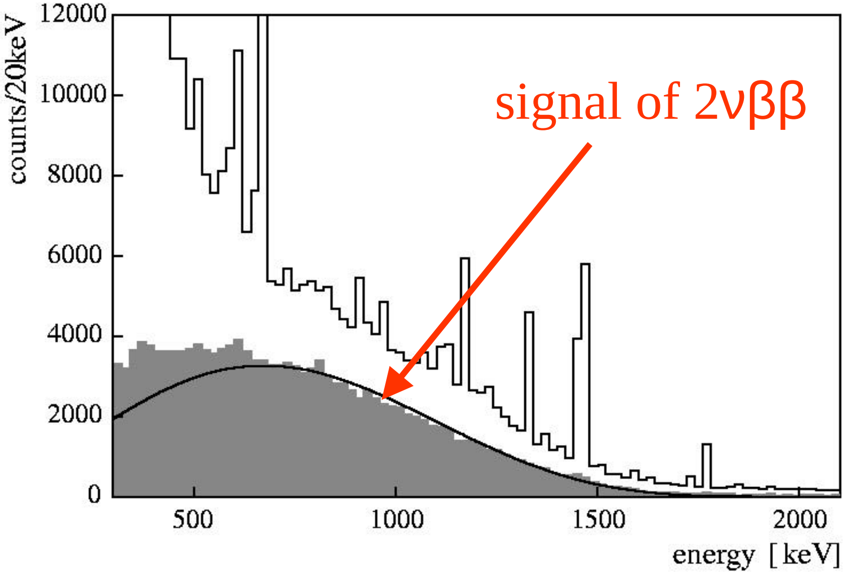


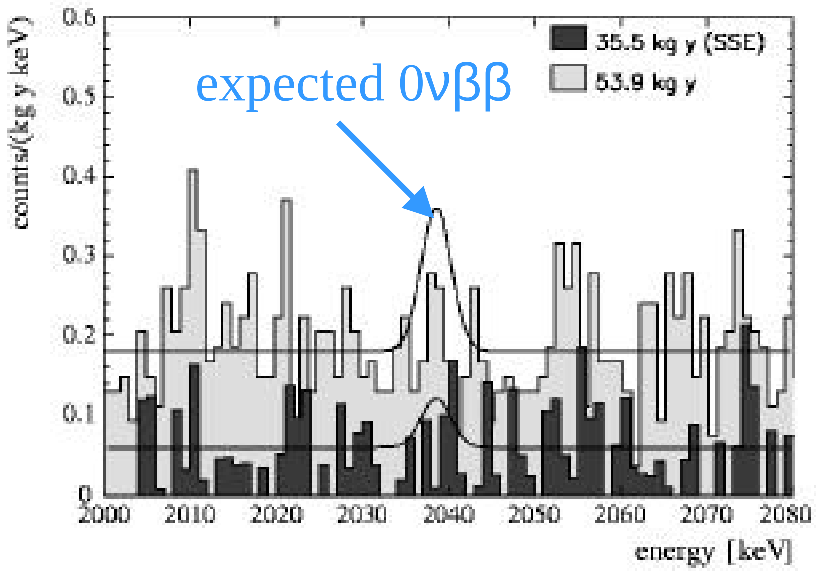
Heidelberg-Moscow (^{76}Ge)

At Gran Sasso laboratory







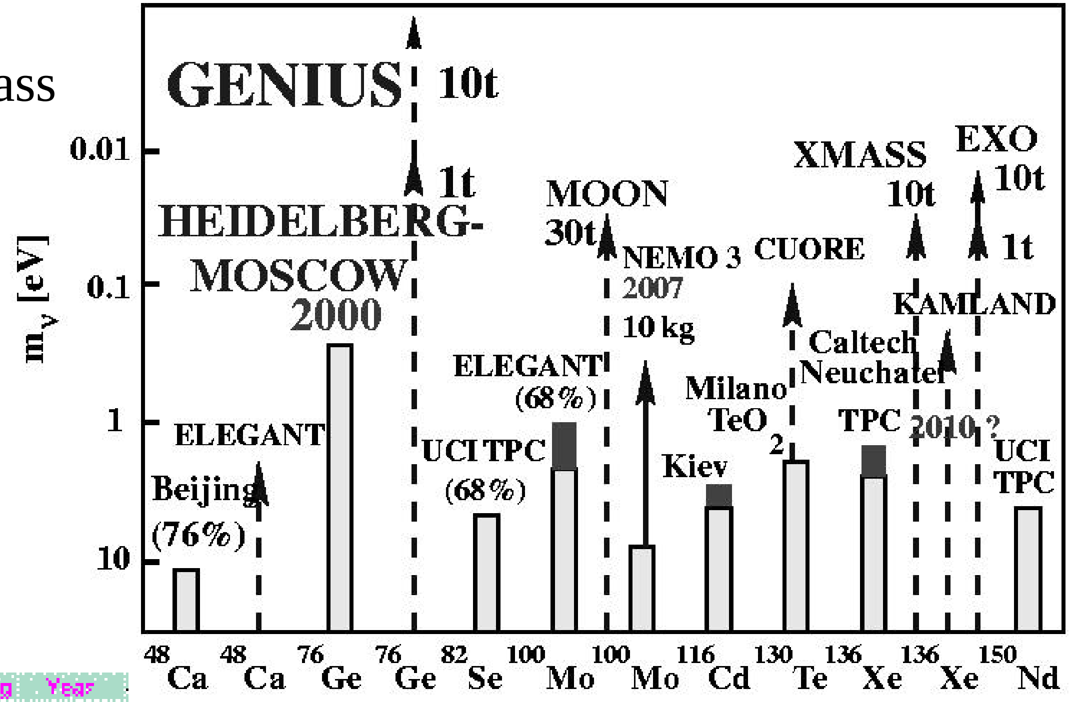


Half-life $T_{1/2}^{2\nu} = 1.55 \pm 0.17 \times 10^{21}$ years

$T_{1/2}^{0\nu} > 3.1 \times 10^{25}$ years (90% CL)

Summary of Double Beta Decay Results

Limits on Majorana neutrino mass



Experiment	nucleid	half life/a	mass limit/eV	majoron coupling	Year
Heidelberg-Moscow	76-Ge	$5.7 \cdot 10^{25}$	0.2 (90%)		1999
IGEX	76-Ge	$1.57 \cdot 10^{25}$	0.33		1999
NEMO	116-Cd 82-Se 96-Zr 100-Mo	$5 \cdot 10^{21}$ $9.5 \cdot 10^{21}$ $1.3 \cdot 10^{21}$ $6.4 \cdot 10^{21}$	9.8 . . 6-18 (90%)	$1.2 \cdot 10^{-4}$? $(2-8) \cdot 10^{-4}$	1998
Elegants	76-Ge 100-Mo 116-Cd 48-Ca	 $4.9 \cdot 10^{22}$ $6.4 \cdot 10^{21}$ $5.2 \cdot 10^{22}$	3 (90%)		1998
Gothard tunnel	136-Xe	$4.4 \cdot 10^{23}$ (90%)	1.8-2.8 (90%)	$1.5 \cdot 10^{-4}$	1993-
Milano-Gran Sasso	130-Te 128-Te	$1.4 \cdot 10^{22}$ (90 %) $8.6 \cdot 10^{22}$ (90 %)	2.6	$6.7 \cdot 10^{-4}$	1995,1998
Solotvina	116-Cd	$7.0 \cdot 10^{22}$ (90 %)	2.6 (90 %)	$1.2 \cdot 10^{-4}$ (90 %)	2000

- The life time is given in second, the column corresponds to the lower limit for neutrinoless double beta decay.
- The limit for the Majorana mass depends on the nuclear matrix elements.
- Majoron column is the upper limit for the neutrino-majoron coupling, deduced from the non-observation of majoron emitting double beta decay.

Latest News

Latest results from the HEIDELBERG-MOSCOW double beta decay experiment

H.V. Klapdor-Kleingrothaus[1,*], A. Dietz[1], L. Baudis[1], G. Heusser[1], I.V. Krivosheina[1], B. Majorovits[1], H. Paes[1], H. Strecker[1], V. Alexeev[2], A. Balysh[2], A. Bakalyarov[2], S.T. Belyaev[2], V.I. Lebedev[2], and S. Zhukov[2]

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Communicated by D. Schwalm

Abstract. New results for the double beta decay of ^{76}Ge are presented. They are extracted from data obtained with the HEIDELBERG-MOSCOW experiment, which operates five enriched ^{76}Ge detectors in an extreme low-level environment in the Gran Sasso underground laboratory. The two-neutrino-accompanied double beta decay is evaluated for the first time for all five detectors with a statistical significance of 47.7 kg y resulting in a half-life of $T_{1/2}^{2\nu} = [1.55 \pm 0.01(stat)^{+0.19}_{-0.15}(syst)] \times 10^{21}$ y. The lower limit on the half-life of the $0\nu\beta\beta$ decay obtained with pulse shape analysis is $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ (3.1×10^{25}) y with 90% C.L. (68% C.L.) (with 35.5 kg y). This results in an upper limit of the effective Majorana-neutrino mass of 0.35 eV (0.27 eV) using the matrix elements of A. Staudt et al.'s work (Europhys. Lett. 13, 31 (1990)). This is the most stringent limit at present from double beta decay. No evidence for a majoron-emitting decay mode is observed.

August 2001 limit:
$T_{1/2}^{0\nu} > 3.1 \times 10^{25}$ years (90% CL)
$M < 0.3$ eV $/c^2$

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUS[1,3],
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The data of the HEIDELBERG-MOSCOW double beta decay experiment for the measuring period August 1990 - May 2000 (54.9813 kg y or 723.44 mol-years), published recently, are analyzed using the potential of the Bayesian method for low counting rates. First evidence for neutrinoless double beta decay is observed giving first evidence for lepton number violation. The evidence for this decay mode is 97% (2.2σ) with the Bayesian method, and 99.8% c.l. (3.1σ) with the method recommended by the Particle Data Group. The half-life of the process is found with the Bayesian method to be $T_{1/2}^{0\nu} = (0.8 - 18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. The deduced value of the effective neutrino mass is, with the nuclear matrix elements from [1], $\langle m \rangle = (0.11 - 0.56)$ eV (95% c.l.), with a best value of 0.39 eV. Uncertainties in the nuclear matrix elements may widen the range given for the effective neutrino mass by at most a factor 2. Our observation which at the same time means evidence that the neutrino is a Majorana particle, will be of fundamental importance for neutrino physics.

January 2002 evidence:
$T_{1/2}^{0\nu} = (0.8\text{-}18.3) \times 10^{25}$ years (95%CL)
1.5×10^{25} years: best value
$M = 0.11\text{-}0.56$ eV $/c^2$ (95% CL)
$= 0.39$ eV $/c^2$: best value

- same data, not all same people…..

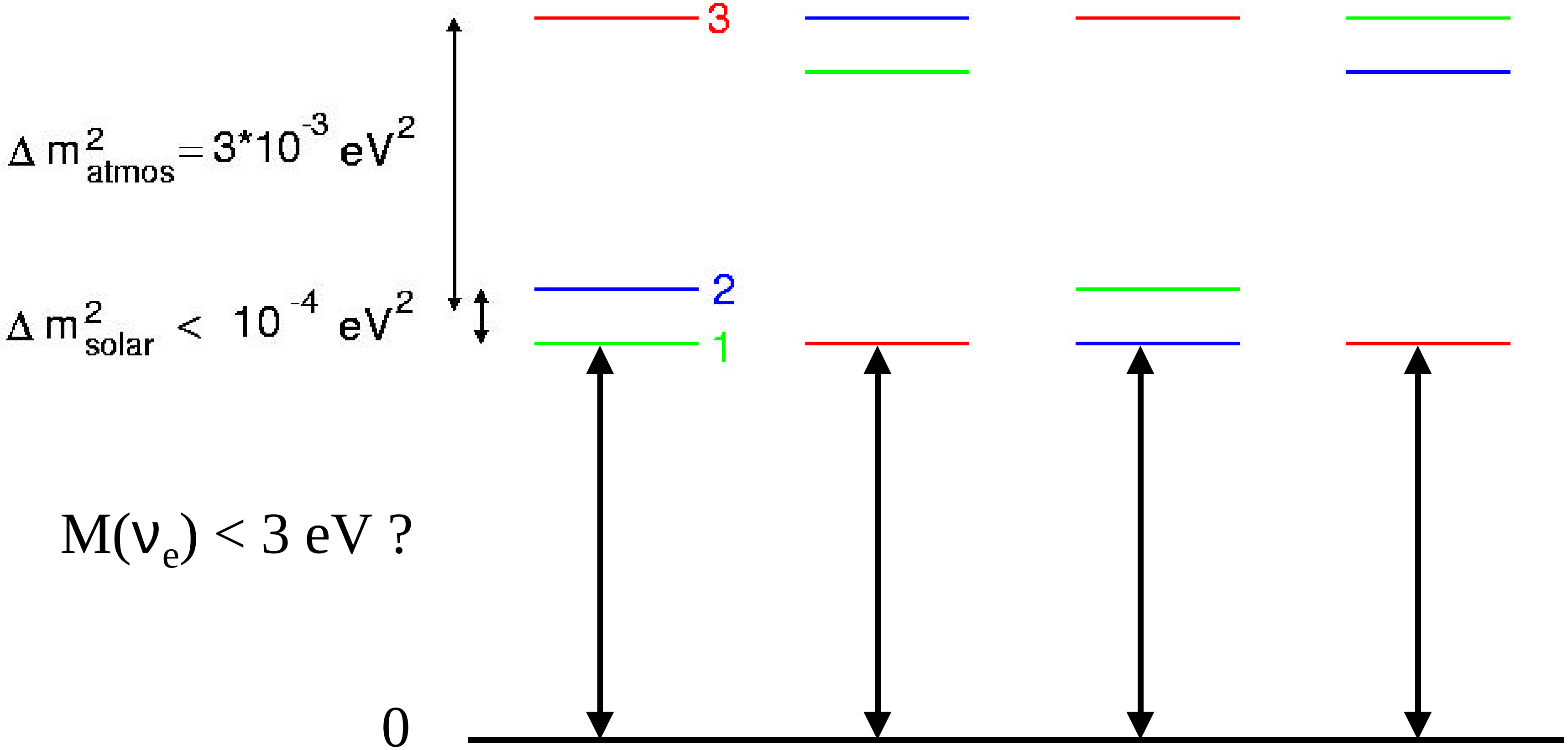
Summary of Particle Data Group 2001

Number of light ν: 2.994 ± 0.012

$M(\nu_e) < 3$ eV $/c^2$
$M(\nu_\mu) < 190$ keV$/c^2$
$M(\nu_\tau) < 18.2$ MeV$/c^2$

Majorana mass $M(\nu_e) < 0.24$ eV $/c^2$
(dependent on Nuclear Matrix Element)

Possible Neutrino Mass Splitting



Zero of mass scale ?

Neutrino Mixing

Analogy with quarks

For massive particles:

flavour eigenstates can be different from mass eigenstates

leptons

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

quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

U : leptonic mixing matrix

V : quark mixing matrix, (CKM matrix)

Standard Model,

U and V unitary 3 × 3 complex matrices: $\Sigma \; U_{k\mu}^* \; U_{k\nu} = \delta_{\mu\nu}$

W decays

leptons

$W \to l\, \nu_l$

$W \to e\,\nu_1$ $½U_{e1}½^2$

$\to e\,\nu_2$ $½U_{e2}½^2$

$\to e\,\nu_2$ $½U_{e3}½^2$

$\to \mu\,\nu_1$ $½U_{\mu 1}½^2$

$\to \mu\,\nu_2$ $½U_{\mu 2}½^2$

$\to \mu\,\nu_3$ $½U_{\mu 3}½^2$

$\to \tau\,\nu_1$ $½U_{\tau 1}½^2$

$\to \tau\,\nu_2$ $½U_{\tau 2}½^2$

$\to \tau\,\nu_3$ $½U_{\tau 3}½^2$

quarks

$W \to q_\alpha\ q_\beta$

$W \to u\,d$ $½V_{ud}½^2$

$\to u\,s$ $½V_{us}½^2$

$\to u\,b$ $½V_{ub}½^2$

$\to c\,d$ $½V_{cd}½^2$

$\to c\,s$ $½V_{cs}½^2$

$\to c\,b$ $½V_{cb}½^2$

$(\not\to t\,X \quad m(t) > m(W))$

Unitarity:

$½U_{e1}½^2 + ½U_{e2}½^2 + ½U_{e3}½^2 = 1$ $½V_{ud}½^2 + ½V_{us}½^2 + ½V_{ub}½^2 = 1$

etc.

Numerical Values

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \qquad \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\begin{pmatrix} & & \\ & ? & \\ & & \end{pmatrix} \qquad \begin{pmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 1.0 & 0.04 \\ 0.006 & 0.04 & 1.0 \end{pmatrix}$$

Possibilities for Leptonic Mixing

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 1.0 & 0.04 \\ 0.006 & 0.04 & 1.0 \end{pmatrix} \quad \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/2 & 1/2 & 1/\sqrt{2} \end{pmatrix}$$

No mixing   like quarks   bi-maximal mixing

If $U_{e3} = 0$ no CP violation (like $V_{ub} = 0$ for quarks)

CP Violation in Neutrino Sector

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

If $U_{e3} = 0$ no CP violation (like $V_{ub} = 0$ for quarks)

Same parameterisation as quark sector:

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

$$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$$

CP conservation: $P(\nu_a \to \nu_b;\, t) = P(\bar{\nu}_a \to \bar{\nu}_b;\, t)$