# Neutrino News from Lab and Cosmos

## *Neutrinoless-Double Beta Decay and Massive Neutrinos*

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*In 1967, Pontecorvo suggested that Davis was going to see 1/2 of solar $\nu$, thinking that a tiny $\Delta m^2$ was almost for warranted. Probably, he also believed that other effects of $\nu$-masses which demand larger masses (such as $0\nu2\beta$, suggested by Furry in 1939) were seen later. Many of us think that this is happened: the only hint for $\nu$ masses comes from oscillation experiments, and $0\nu2\beta$ is still to be discovered. This raises a number of questions: Which links exist between the various manifestations of $\nu$ masses? How can we use 'measurements' to guess where $0\nu2\beta$ is? Which are the cases of special experimental interest? Are they likely? We would like to discuss these questions, with the guide of recent experimental achievements and a bit of theory/prejudice.*

# $1^{st}$ part

## Neutrinoless double beta decay ($0\nu2\beta$)

- Which Majorana mass
- Nuclear physics aspects

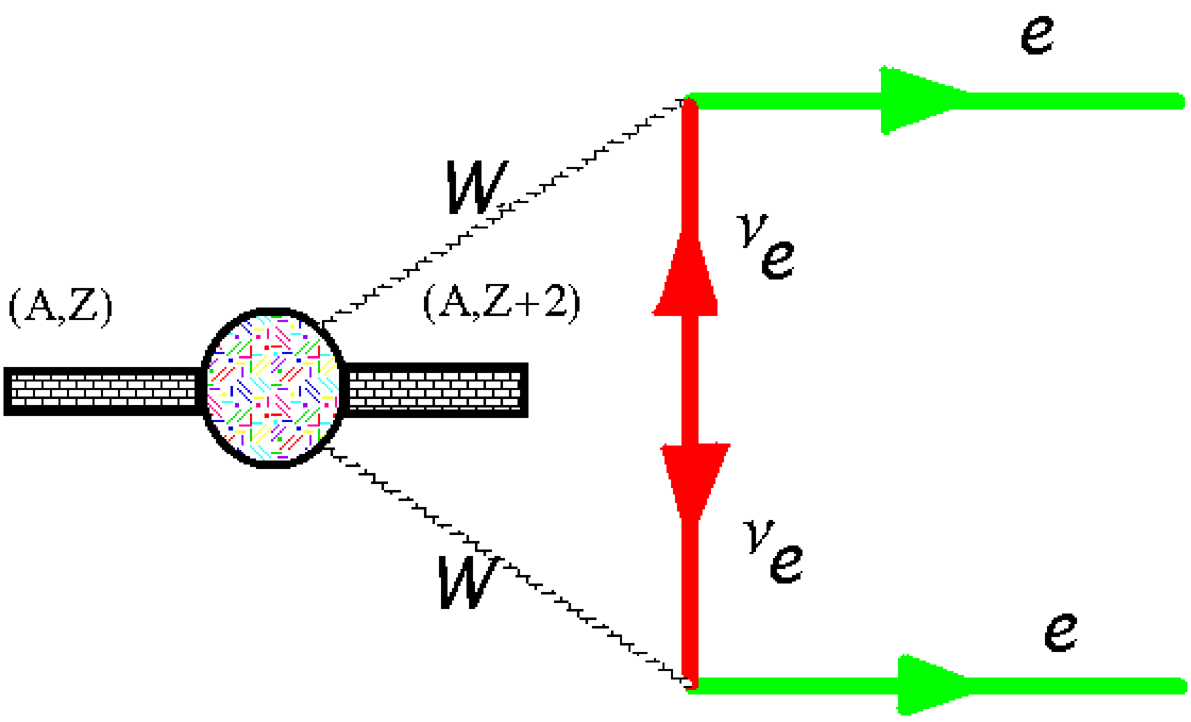
## Techniques for investigation

- Few experimental concepts
- Remarks on a recent claim
- Summary of present achievements

The double beta decay processes $(n\nu 2\beta)$ are:

$$(A,Z) \to (A,Z+2) + 2\, e^- + n\,\nu, \quad n = 0,2$$

$0\nu 2\beta$ gets a contribution from $\nu$ masses (it is $\Delta L_e = 2$):

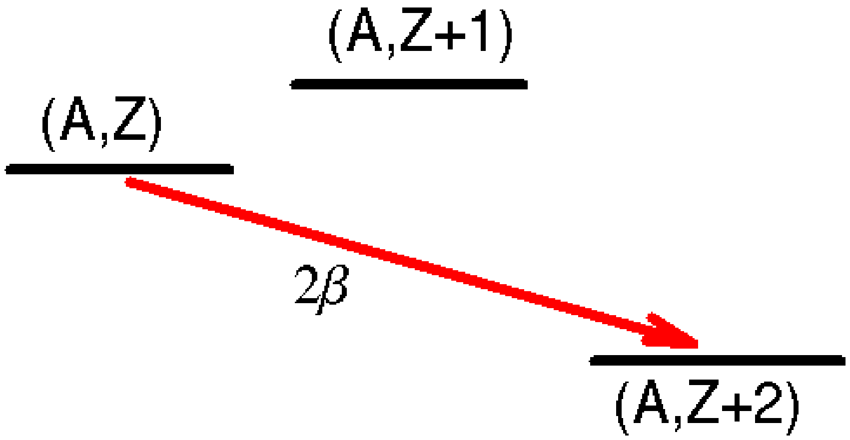



The arrow clash, unfamiliar to people acquainted to standard model fermionic currents like $\bar\psi\gamma^a\psi'$, points out the presence of Majorana masses. More precisely, we need:

$$M_{ee} \neq 0$$

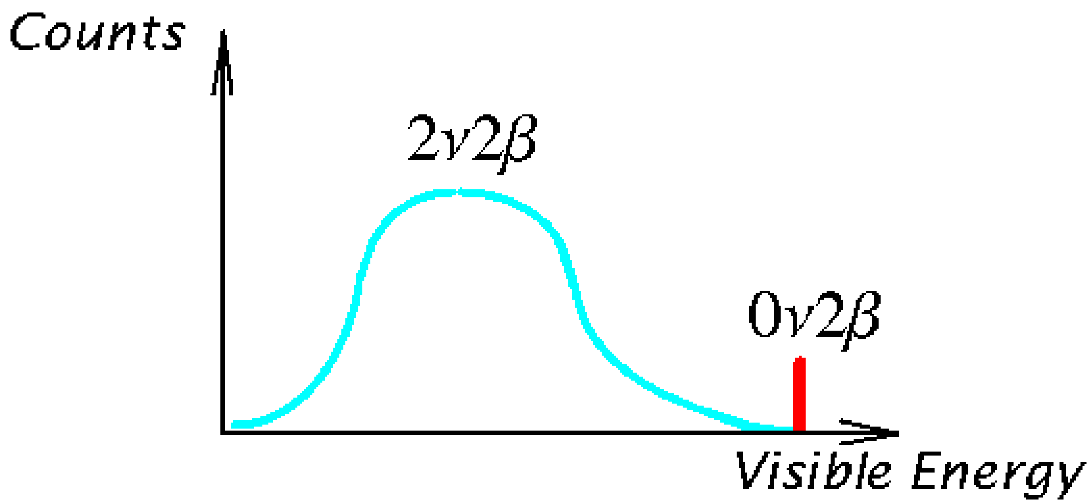
(we probe just 1 element of mass matrix–not $M_{e\tau}$, $M_{\mu\mu}$...)

Some even-even nuclei ($^{76}$Ge, $^{130}$Te, $^{100}$Mo ...) have ground levels so arranged:




thus, $\beta$ decay is forbidden, but $2\beta$ is not.

(In absence of massive $\nu$'s, or other non-standard physics, only $2\nu2\beta$ takes place). Spectra look as follow:




In real life: limited energy resolution and background!

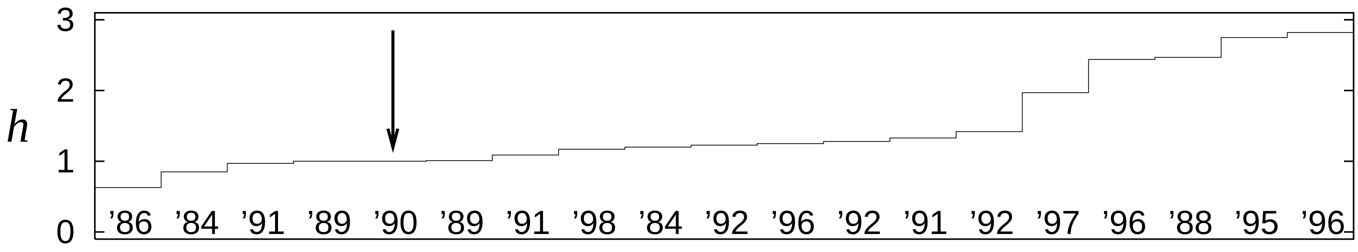
The observable quantities are the transition rates, $\Gamma_{2\nu2\beta}$ and $\Gamma_{0\nu2\beta}$. When we relate $\Gamma_{0\nu2\beta}$ to $\nu$ masses, we need to know the nuclear matrix elements $\mathcal{M}$:

$$\Gamma_{0\nu2\beta} = G \cdot \left|\mathcal{M}^2\right| \cdot \left|M_{ee}^2\right|$$

If, using $\mathcal{M}(0)$, we get the limit (or measurement) $|M_{ee}(0)|$, changing nuclear matrix element we get:

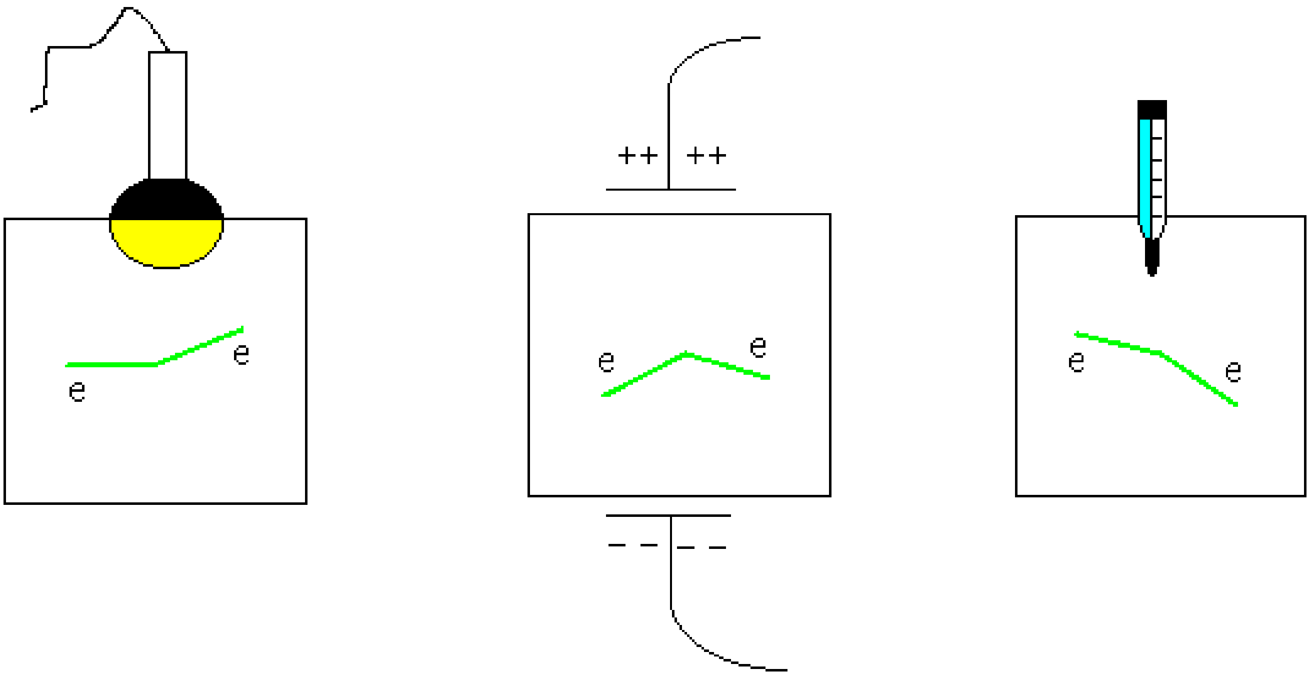
$$|M_{ee}| = |M_{ee}(0)| \cdot \left|\frac{\mathcal{M}(0)}{\mathcal{M}}\right| \equiv |M_{ee}(0)| \cdot h$$

Agreement between different calculation is still not perfect. Take (for $^{76}$Ge) $\mathcal{M}(0)$=Staudt *et al.* '90:




Some checks can be done with $\Gamma_{2\nu2\beta}$, but it seems that the use of various nuclei is really mandatory.

We need to measure the (monochromatic) energy well:

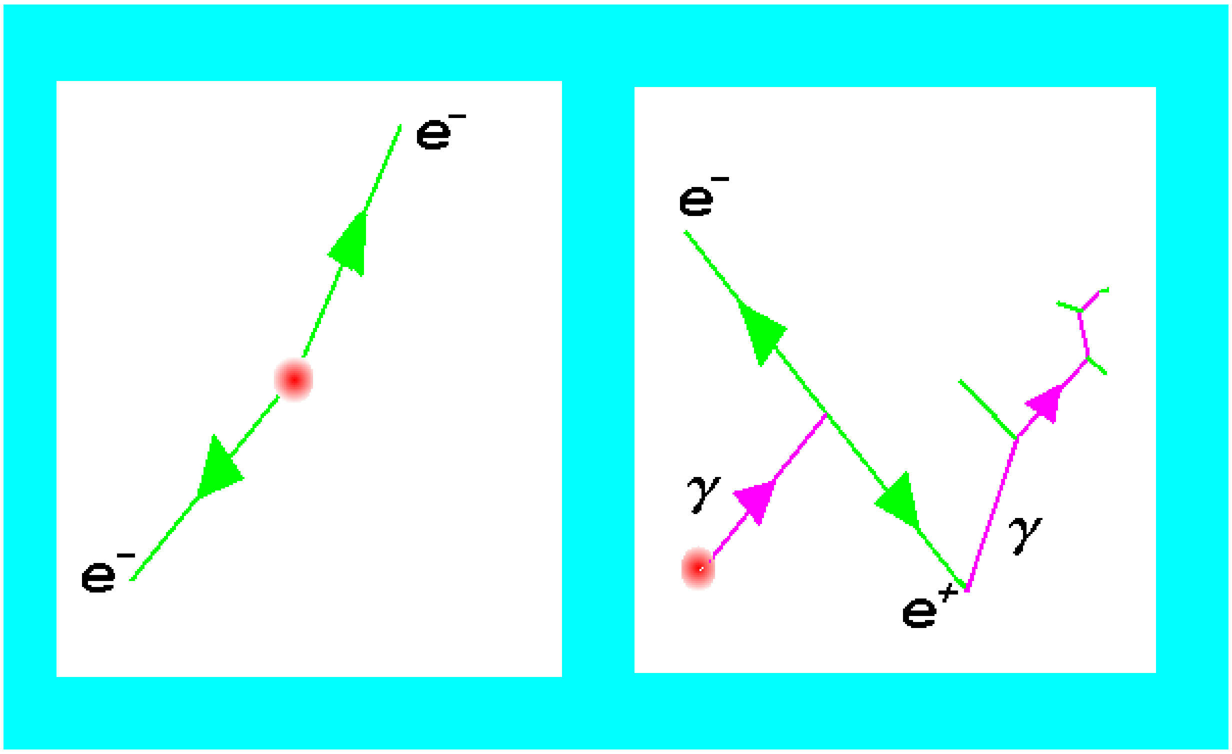



The $2^{nd}$ concept includes the $^{76}$Ge technique proposed in 1967 by Fiorini *et al.* It yielded the best limit (Heidelberg-Moscow (HM) experiment at LNGS, IGEX). Seriously considered for future steps (Majorana, GENIUS, GEM).

Fiorini himself and his group push the $3^{rd}$–bolometer–concept (MIBETA) with tellurium. This produced the next better result, and will lead to future large experiment CUORE (the mini-version, CUORICINO, starting this year).

Many other experiments and proposals are based on (various combinations of) these concepts and other important considerations (background control, isotopic enrichment, double tag, etc.) e.g. NEMO III, MOON, EXO...

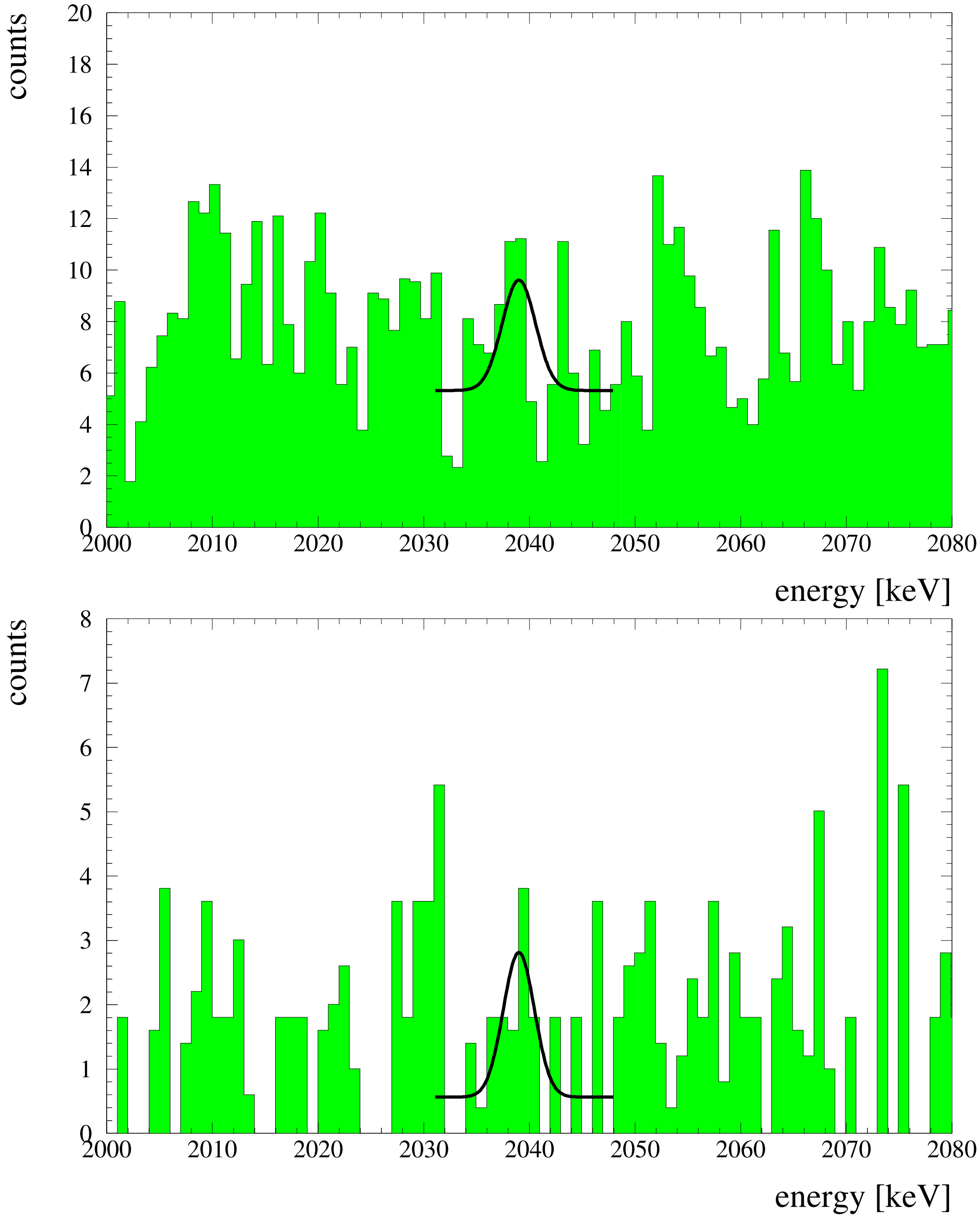
"Pulse shape analysis" for $^{76}$Ge is a good example of how the background can be controlled.
E.g., $\gamma$ radiation can deposit monochromatic energy in the crystal:




but the energy is deposited in a wider area, and the electric pulse has a different time structure, usually.

This way, HM reduced the background by a factor of $\sim 6$ (IGEX exploited successfully PSA too.)

A hearth-breaking claim of “evidence for $0\nu2\beta$” [published on 3 refereed Journals, and quoted by PDG] has been made recently (Klapdor *et al.*, 2001), based on the HM data shown below (without and with PSA/0.55); also shown signal+background fit



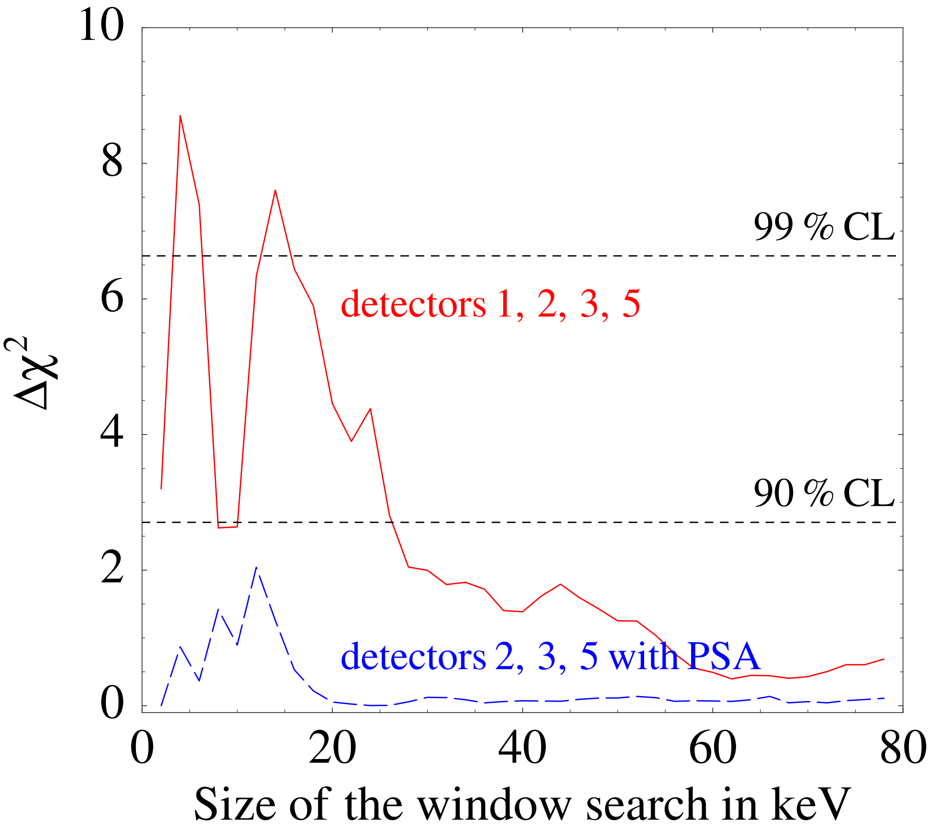

Position of $0\nu2\beta$ is at 2039 keV; faint lines of $\gamma$'s from $^{214}$Bi are expected at 2011, 2017, 2022 and 2053 keV.

This interpretation is not universally accepted, since:

⋆ Expected gamma lines are poorly seen, and unexpected “lines” are in other locations.

⋆ The PSA reduces the background, but also the putative signal by a very similar amount.

⋆ Claimed significance is not high “2.2-3.1 $\sigma$”; however it strongly depends on analysis window.



Best 90 % bounds (as quoted by the Authors):

| nucleus | $\lvert M_{ee}\rvert$ in eV | Experiment |
|---|---|---|
| $^{76}$Ge | 0.35 | HM |
| $^{76}$Ge | 0.33-1.35 | IGEX |
| $^{130}$Te | 0.9-2.0 | MIBETA |
| $^{100}$Mo | 2.1 | ELEGANT V |
| $^{136}$Xe | 1.8-5.2 | GOTTHARD |

Some expected 5 y sensitivities (with Staudt'90)

| nucleus | $\lvert M_{ee}\rvert$ in meV | Experiment |
|---|---|---|
| $^{76}$Ge | 15 | GENIUS |
| $^{76}$Ge | 25 | MAJORANA |
| $^{130}$Te | 27 | CUORE |
| $^{100}$Mo | 36 | MOON |
| $^{136}$Xe | 52 | EXO |

(For more information, see O.Cremonesi, hep-ex/0210007 and the more complete table of the talk of W.Haxton)

# *$2^{nd}$ part*

## The Majorana mass hypothesis

How many parameters we have

$|M_{ee}|$ and the other observables

## Two cases of special interest

A model with 4 neutrinos

A model with 3 neutrinos

- Comparing the masses of $\beta$ and $0\nu2\beta$
- Remarks

A Majorana mass has 9 (or more in general, $n^2$) physical parameters:

$$\mathcal{L} = \frac{1}{2}\, \mathbf{M}_{\ell\ell'}\, \nu_\ell^t\, C^{-1}\, P_L\, \nu_{\ell'} + h.c. \qquad \ell, \ell' = e, \mu, \tau, s, \ldots$$

Useful to decompose it as follows:

$$\mathbf{M}_{\ell\ell'} = \sum_{i=1}^{n} U_{\ell j}^{*} \cdot m_j \cdot \mathrm{e}^{i\xi_j} \cdot U_{\ell' j}^{*}$$

My phase convention is $U_{ei} \in I\!\!R$: in this way, the oscillation phase(s) is (are) not relevant for $0\nu 2\beta$

The parameters that could be measured are:

- $|\mathbf{M}_{ee}|$ from neutrinoless double beta decay.
- 3 (or $\frac{n(n-1)}{2}$) angles $\theta_{ij}$, and 1 (or $\frac{(n-1)(n-2)}{2}$) phase from oscillations.
- 2 (or $n-1$) $\Delta m_{ij}^2 = m_i^2 - m_j^2$'s from oscillations.
- 1 or more parameters from $\beta$ decay.

Today we know 2 (optimistically 4 or even more) of them; and we are not certain that $n = 3$

Besides Majorana numerology, there are only a few general results, as:

1. The mass scale probed in $\beta$ decay is larger than than the one probed in $0\nu 2\beta$

   (not very useful)

2. If $\theta_{sun} \leq 45°$ and there are 3 $\nu$, $M_{ee}$ can be always zero for certain $m_i$, $\xi_i$ and mass spectra

   (this is important, it implies we can say little *unless* we adopt some theoretical framework).

3. $\beta$ decay and oscillations cannot see Majorana phases

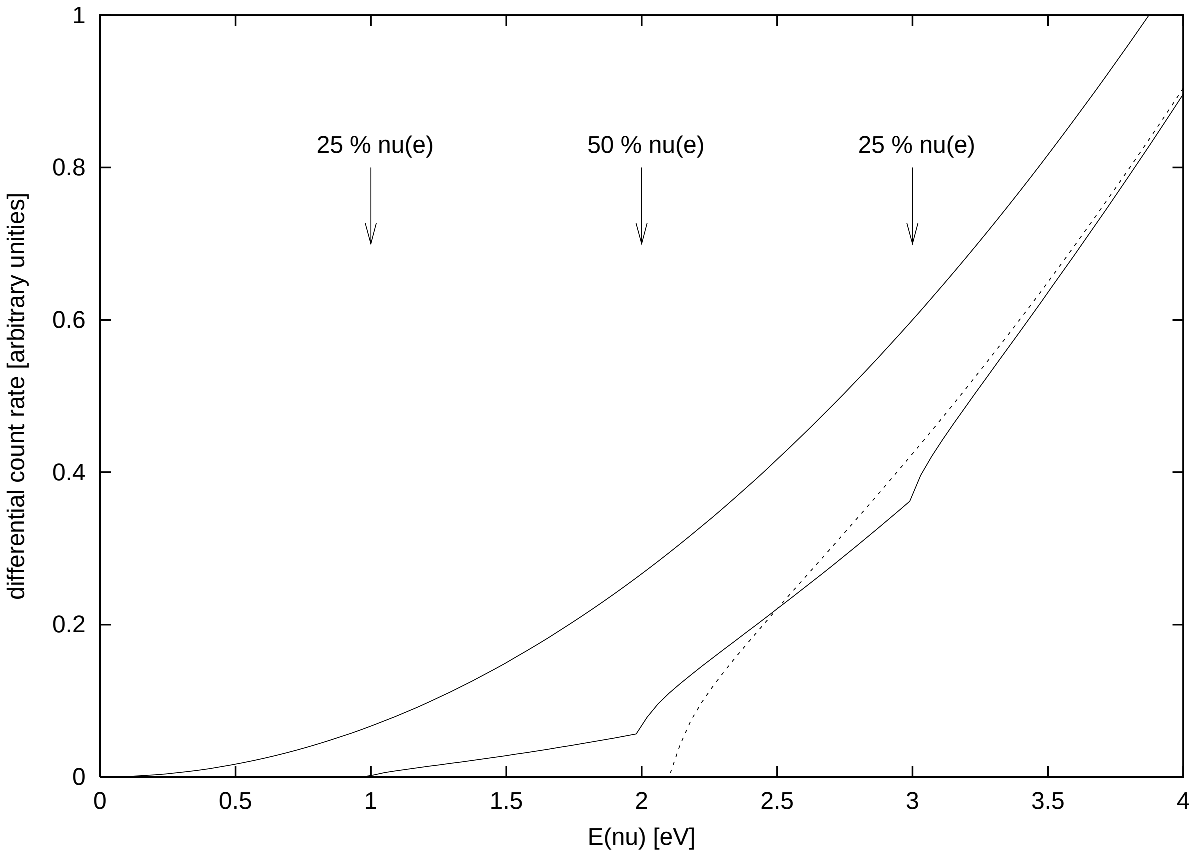
   (this implies that $0\nu 2\beta$ is *unique*)

Instead of proofs, or making zoology of possibilities, we will focus on 2 specific but important cases, commenting on general features whenever possible.

Before, we discuss the link of our $0\nu 2\beta$ key parameter

$$|M_{ee}| = |U_{ei}^2 \; m_i \; e^{i\xi_i}|$$

with what is measured in $\beta$-spectra (see illustration)




We must distinguish two cases.

*1*$^{st}$ If all mass levels fall within energy resolution $\delta E$, one parameter (=electron weighted mass) is sufficient:

$$\Gamma \approx \Gamma( \; U_{ei}^2 \; m_i^2 \; )$$

*2*$^{nd}$ If one or more mass levels stand up, we need at least *2* parameters, e.g.:

$$\Gamma \approx (1 - U_{eh}^2) \; \Gamma(0) + U_{eh}^2 \; \Gamma(m_h^2)$$

# A 4 neutrino model

The highest "island" permitted by LSND + KARMEN2 has a big $\Delta m^2$. In a 3+1 scheme:

$$m_h^2 = 7 \text{ eV}^2, \quad U_{eh}^2 = 10^{-3}$$

$\delta E \approx 1$ eV at KATRIN $\Rightarrow$ we are in *2$^{nd}$* case ("resolved" energy spectrum)

Sensitivity was estimated assuming a number of missing events at endpoint; this is $\propto m_{\nu_e}^3$. Here, the number of missing events is $\propto U_{eh}^2 m_h^3$. Comparing

$$m_{\nu_e} \approx 0.3 \text{ eV with } \sqrt{7} \text{ eV} \times (10^{-3})^{1/3} = 0.26 \text{ eV}$$

this case looks promising!

(but a new calculation of sensitivity would be advisable)

This case can be tested also by $0\nu 2\beta$, since:

$$|M_{ee}| \approx |U_{eh}^2|\; m_h = 26 \text{ meV}$$

(the $1^{st}$ thing to know is: if MiniBooNE agrees).

## A 3 neutrino model

Consider now the usual 3 $\nu$'s, with "degenerate" spectrum, that is common large mass $m_0$ on the top of small splittings (that explain solar and atm. oscillations)

$0\nu 2\beta$ has a range of values due to Majorana phases

$$|c_{13}^2 \cos 2\theta_{12} - s_{13}^2| \leq \frac{|M_{ee}|}{m_0} \leq 1$$

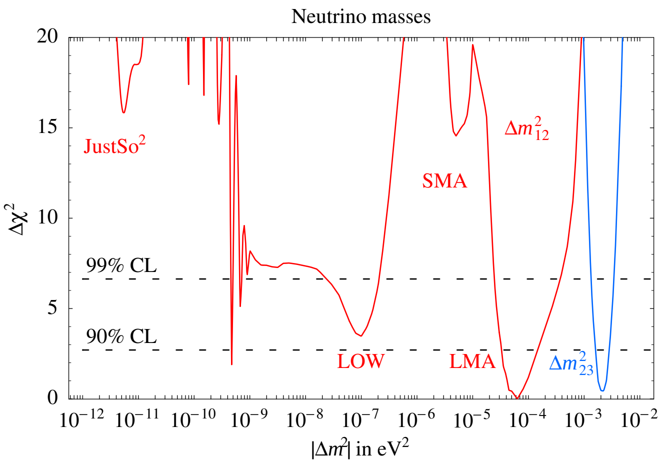
for small $\theta_{13}$, lower limit is just $\sqrt{1-\sin^2 2\theta_{12}}$

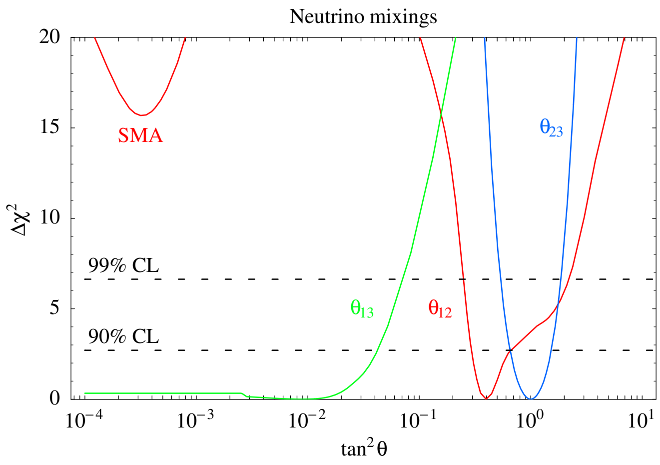
It is just obvious that $\beta$-decay measures $m_\beta = m_0$

So, it is possible to cook some facts into an inference:

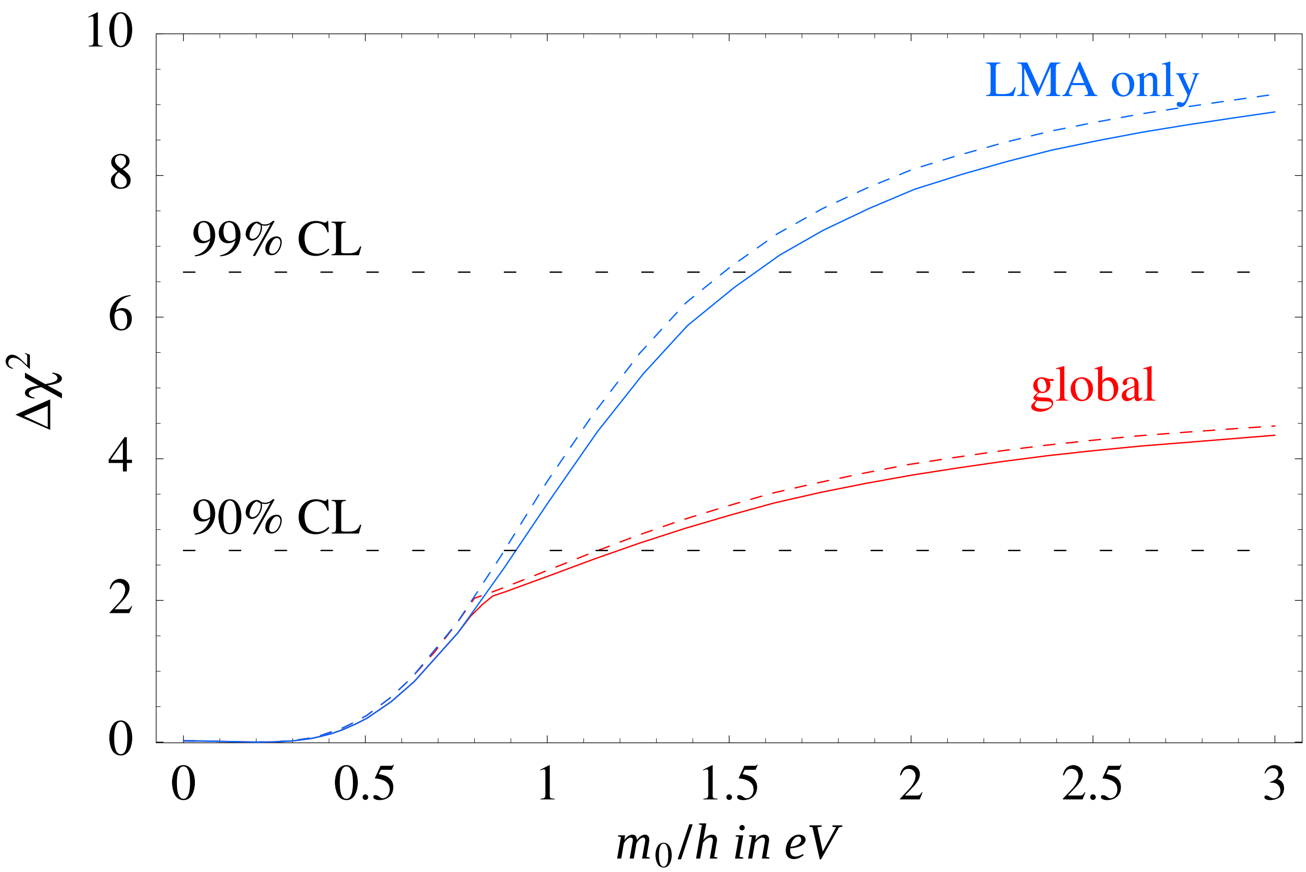
1. atmospheric $\nu$ data + CHOOZ -Palo Verde give a bound on $\theta_{13}$;
2. solar $\nu$ data give $\theta_{12}$;
3. from the bound on $m_{0\nu 2\beta} = |M_{ee}|$, we can get a *conservative* bound on $m_\beta = m_0$

Reminder of what we know on $\Delta m^2$ (left) and on mixing angles (right) in 3 flavor context, from solar and atmospheric $\nu$:




So, the weakest bound on $m_0$ from $0\nu 2\beta$ and oscillations is:




(See F.Feruglio etal, Nucl.Phys.B637:345, 2002)

This calculation is meant to prove that:

There is a direct competition between the searches of $\nu$ masses based on (endpoint) $\beta$ spectrum and $0\nu2\beta$, under a number of conditions:

- Neutrinos are Majorana particles;
- There are 3 $\nu$ that account for solar and atm. oscillations (in this case, MiniBooNE won't find a signal of oscillation);
- The indication for LMA is meaningful (in this case, KamLAND will find a signal).

Incidentally, this laboratory bound is compatible with cosmological 2dF's, to be discussed by O.Elgaroy.

# Remarks

There is a number of theoretical troubles and doubts on the case $m_i \approx m_0$ (degenerate $\nu$):

1. Most simply, degenerate spectrum *looks* alien!
2. Hierarchical Yukawa's try to destabilize the spectrum by terms $m_0^2 \cdot \frac{y_\tau^2}{(4\pi)^2} \log\left(\frac{Q}{Q_0}\right) \gg \Delta m_{ij}^2$. This is not *always* true, however.
3. Tiny Planck induced masses $\langle H\rangle^2/M_{\rm Pl}$ multiplied by $m_0$ might be $\gg \Delta m_{ij}^2$, *if* they are present (LMA, however, is quite safe from these risks)
4. Leptogenesis + canonical seesaw do not want a big $m_0$ (Buchmüller). But neither of them is *unavoidable*.
5. ...

In short: the odds seem against the case of degenerate $\nu$, but the safest thing would be to refute it on experimental basis.

If one wants to consider these schemes seriously, and in view of 2. and 3., it might be better to have big $\Delta m_{ij}^2$–say, LMA rather than LOW–or no solar $\nu$ at all

# Many "ifs" for the discussion

⋆ The practical way to explore the hypothesis that neutrinos have Majorana mass is $0\nu 2\beta$.

⋆ There is an impressive experimental effort in act, with promises to reach the 10 meV level for $|M_{ee}|$. (It would be important to pair these with improvements on nuclear physics side).

⋆ The connection with oscillations is *not* particularly tight; the naive expectation $|M_{ee}| \sim (\Delta m^2_{ij})^{1/2}$ can obtain–or cannot. However, one of the most important things to check out is: whether the solar mixing angle is maximal. It is just crucial to see if LSND findings are supported by MiniBooNE.

⋆ The connection with beta decay is perhaps more interesting. One should not forget that $0\nu 2\beta$ experiments plan to achieve experimental sensitivities more than an order of magnitude higher, and already now, there is "competition" between the two results.

⋆ There are some theoretical cases that would have a big impact on experiments—if they are realized.

*Thanks!*

# *Other material*

## Measuring neutrino masses

Solar $\nu$ after KamLAND and Borexino

Examples of $\beta$ spectra

Another presentation of $0\nu2\beta$ bound

Inverted spectrum

All 3 $\nu$ spectra at glance (V1 and V2)

## Really theory

Type1 and type2 seesaw

A model with flavor symmetry

An SO(10) model for neutrino masses

# Present and near future

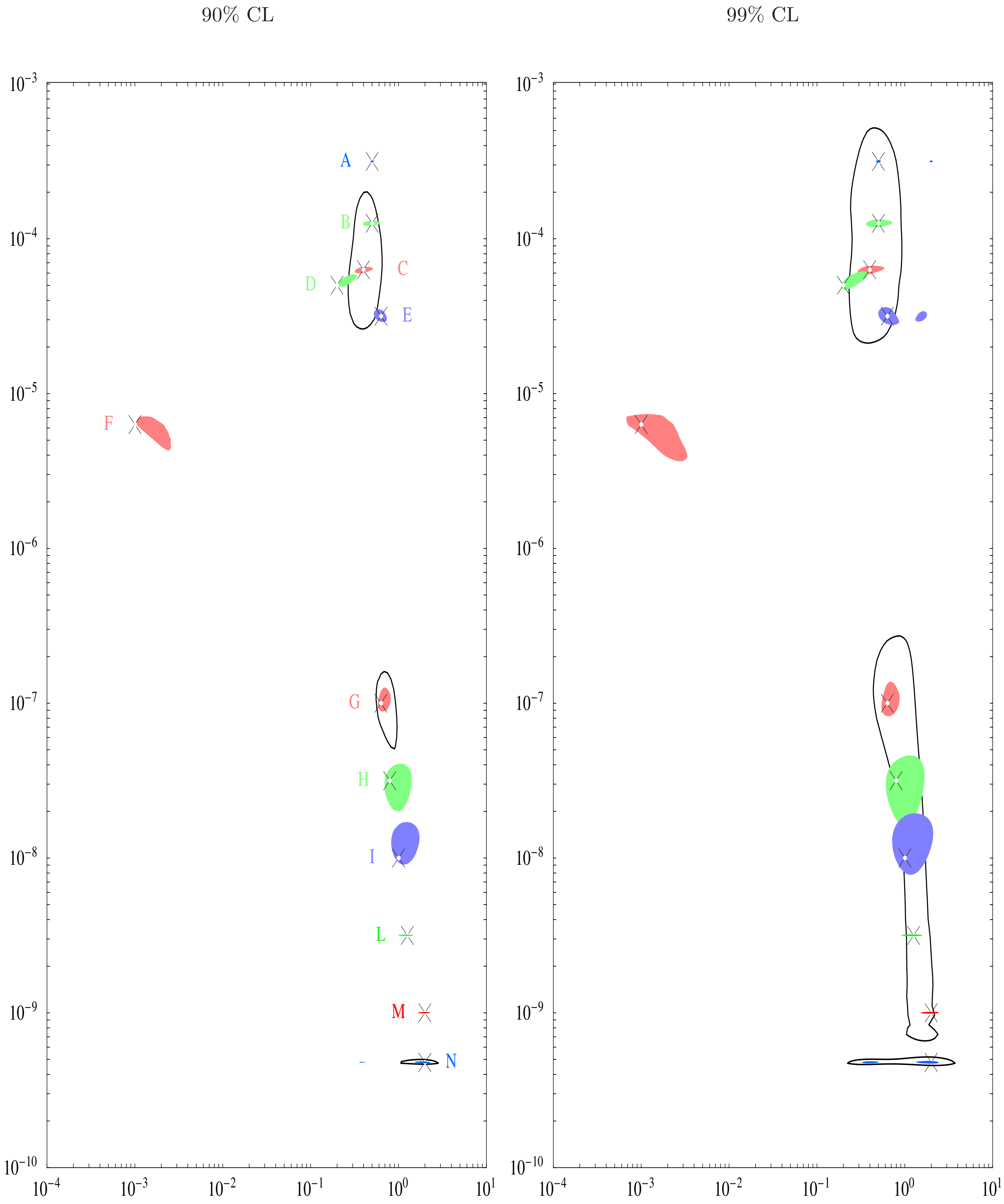
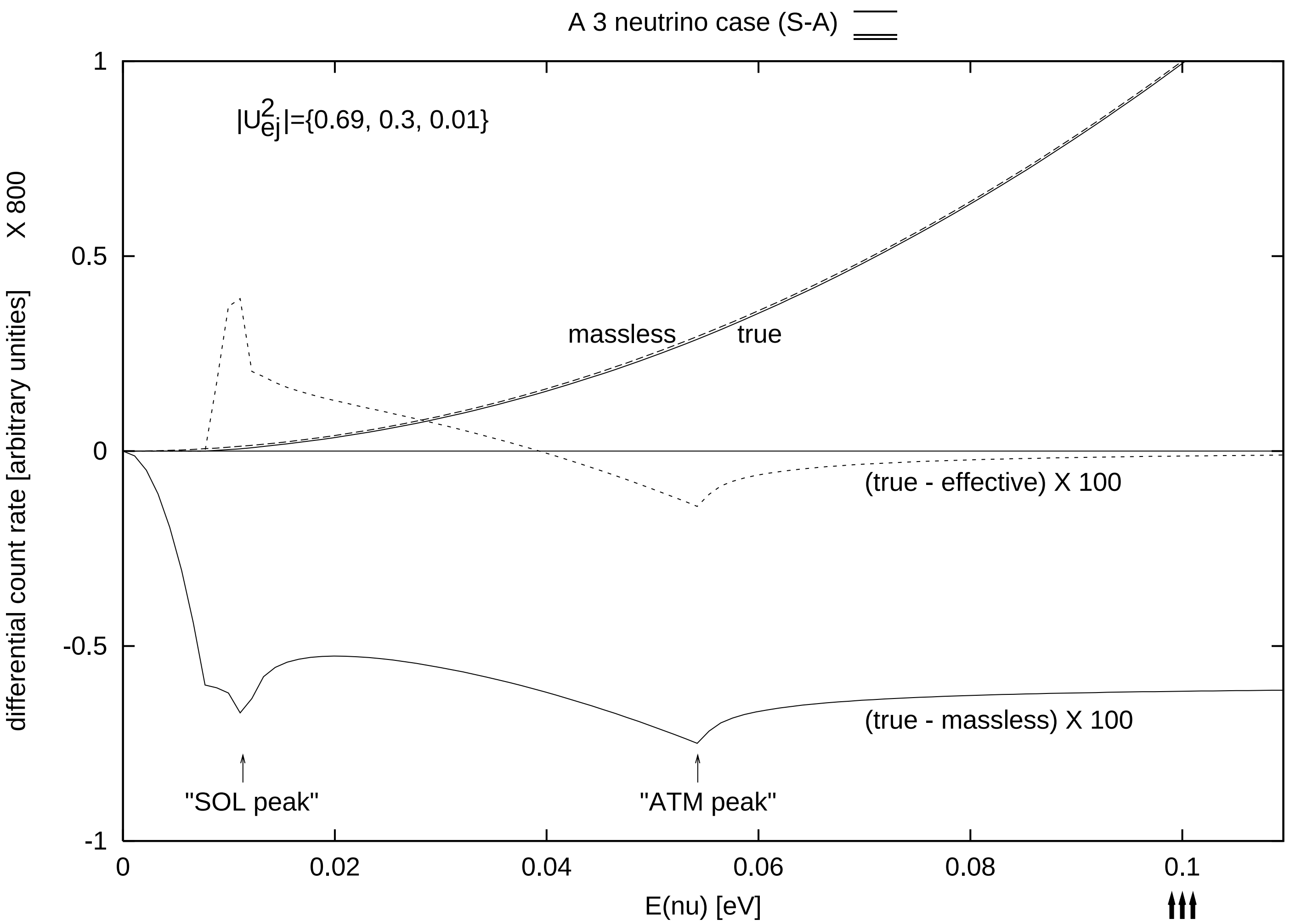
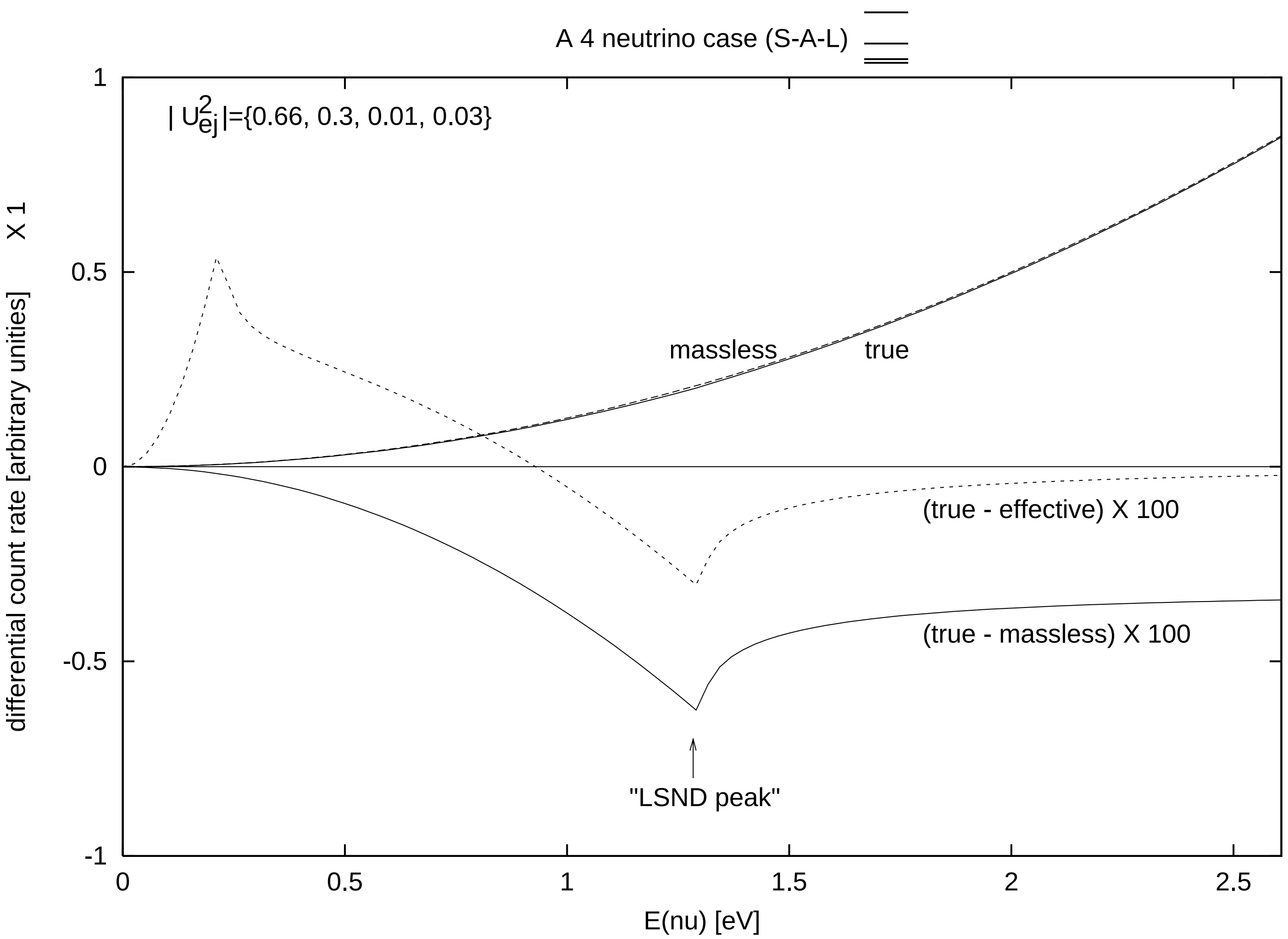
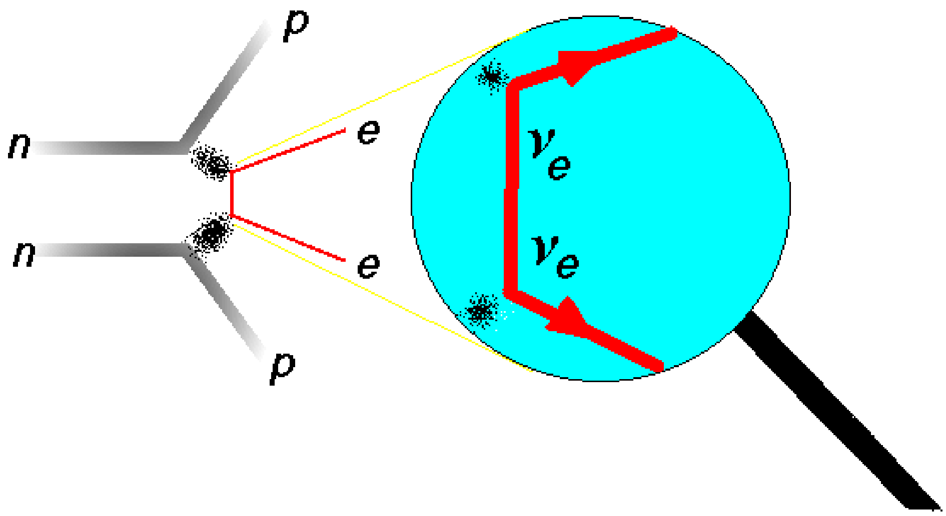



Figure 1: *The continuous lines show the present global fit of solar data in the* $(\tan^2\theta, \Delta m^2/\mathrm{eV}^2)$ *plane. The coloured regions are the simulated near-future fits (after KamLAND and Borexino) for few benchmark points, marked as* $\times$ *and listed in table 1. The left (right) plot shows fits at* 90% (99%) *confidence level. The true oscillation solution is identified in all cases (LMA, SMA, LOW, QVO, VO). Some simulated fits give very small regions: their main features can be read from table 1.*


A 3 neutrino case (S-A)
$|U^2_{ej}|$={0.69, 0.3, 0.01}
differential count rate [arbitrary unities] X 800
massless
true
(true - effective) X 100
(true - massless) X 100
"SOL peak"
"ATM peak"
E(nu) [eV]
1
0.5
0
-0.5
-1
0
0.02
0.04
0.06
0.08
0.1


A 4 neutrino case (S-A-L)
$| U^2_{ej}|$={0.66, 0.3, 0.01, 0.03}
differential count rate [arbitrary unities] X 1
massless
true
(true - effective) X 100
(true - massless) X 100
"LSND peak"
E(nu) [eV]
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5

# Neutrinoless double $\beta$ decay




The ee-element of the mass matrix $\mathbf{M}_{ee}$ triggers $0\nu 2\beta$.
Present best limit 350 meV; may be improved to 20 meV.

If $m_1$ is big, the lower bound is:

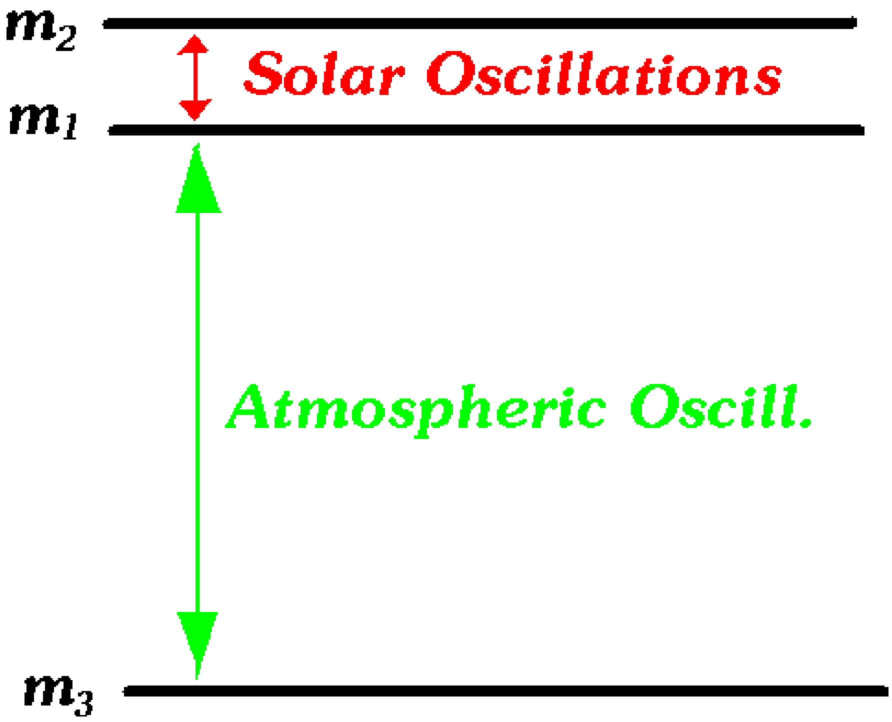
$$|\mathbf{M}_{ee}| \geq \max(c_{13}^2 |\cos 2\theta_{12}| - s_{13}^2, 0) \times m_1$$

This means that:

- If we know the angles well enough, we convert the bound on $\mathbf{M}_{ee}$ on a bound on $m_1$
- In other words, we learn on $\beta$-decay parameter from $0\nu 2\beta$ decay + oscillations.

# Inverted hierarchy

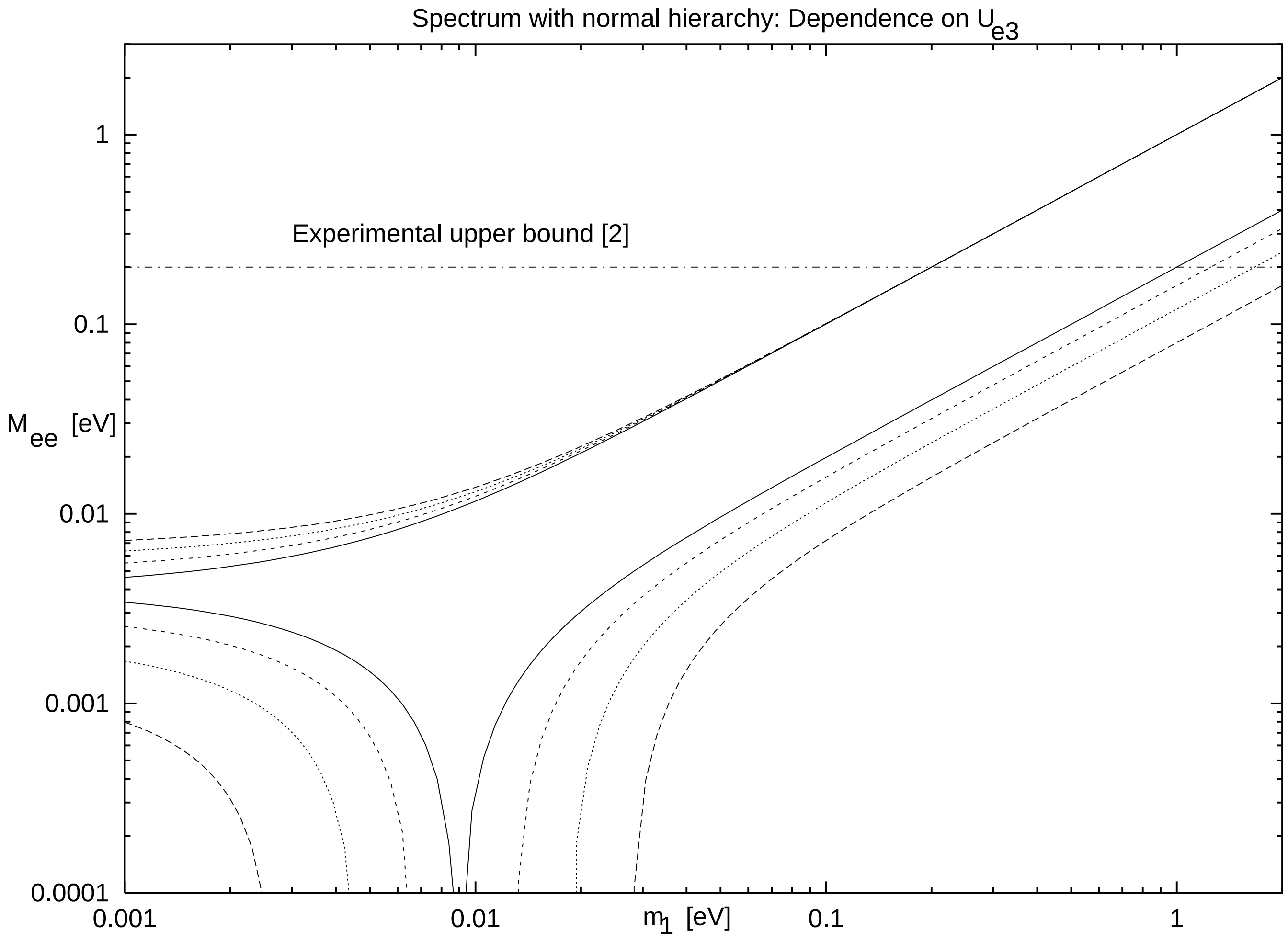
A case that can be investigated by future $0\nu2\beta$ experiments is the inverted hierarchy spectrum

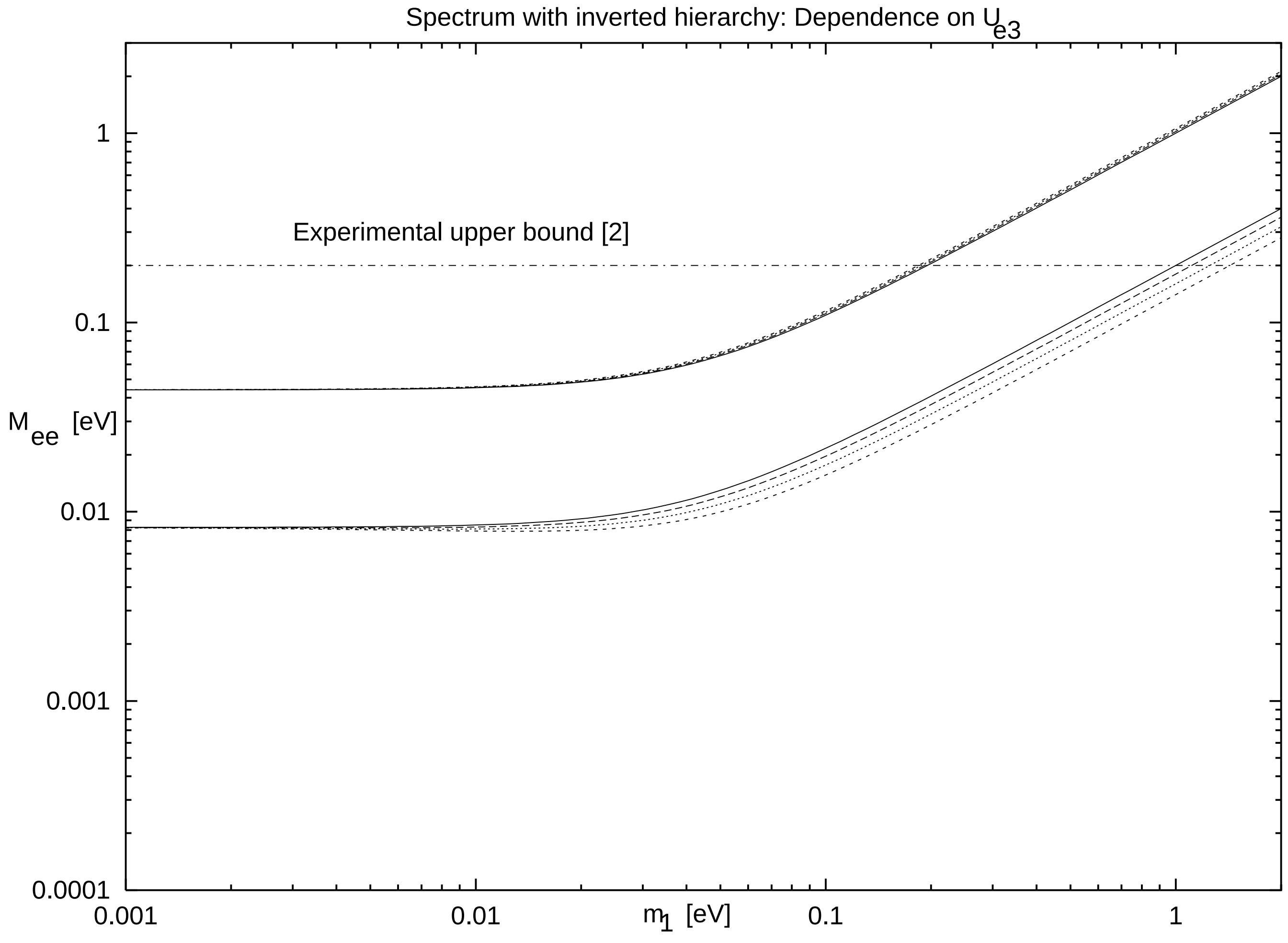


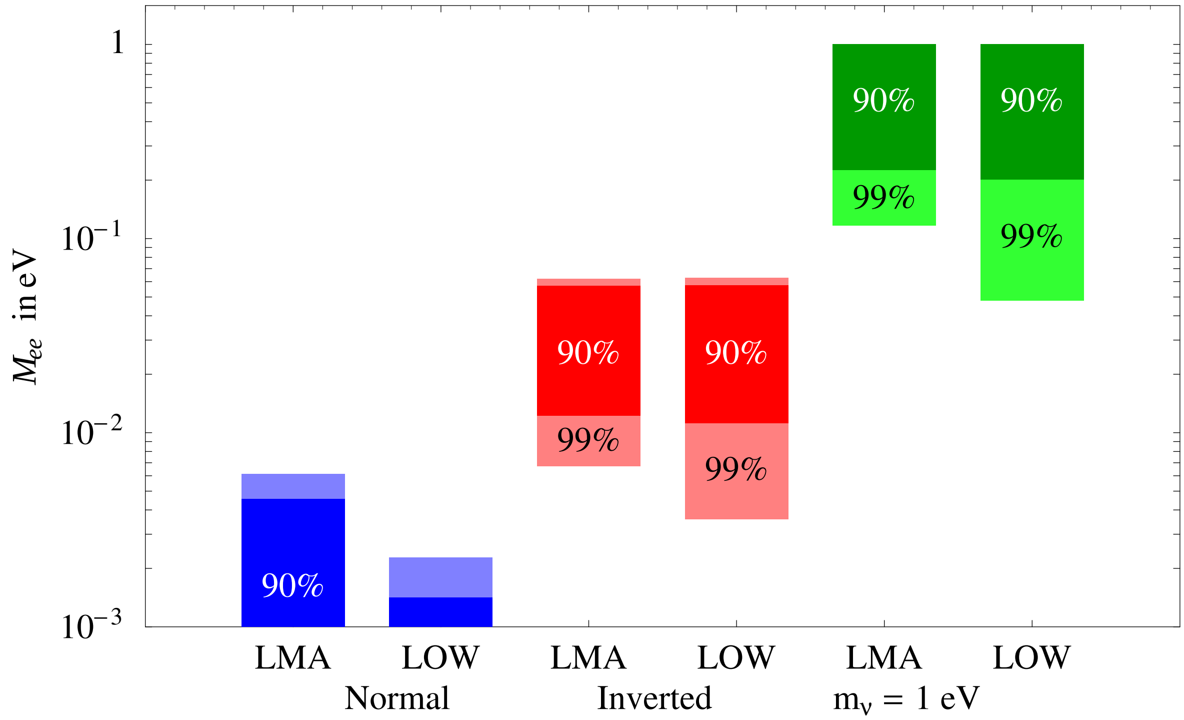

(we have in mind the case when lightest $\nu$ is very light)

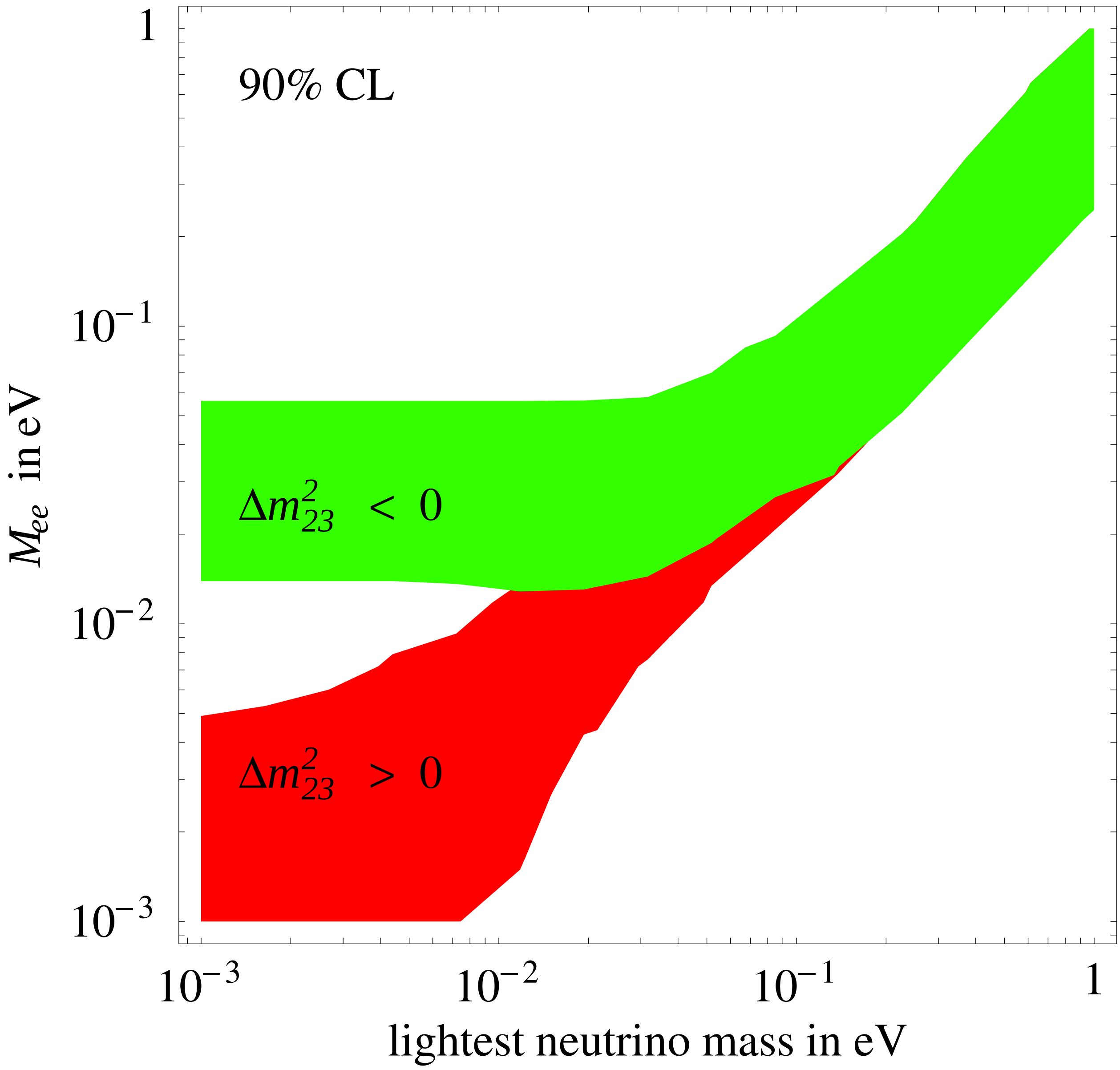
This case can be ruled out (confirmed) by oscillations, discovering $\theta_{13}$ and matter effect.

However, even if this fails (e.g. $\theta_{13}$ is tiny), but solar mixing angle is non-maximal, it can be fully explored by $0\nu2\beta$ search at 10 meV level.

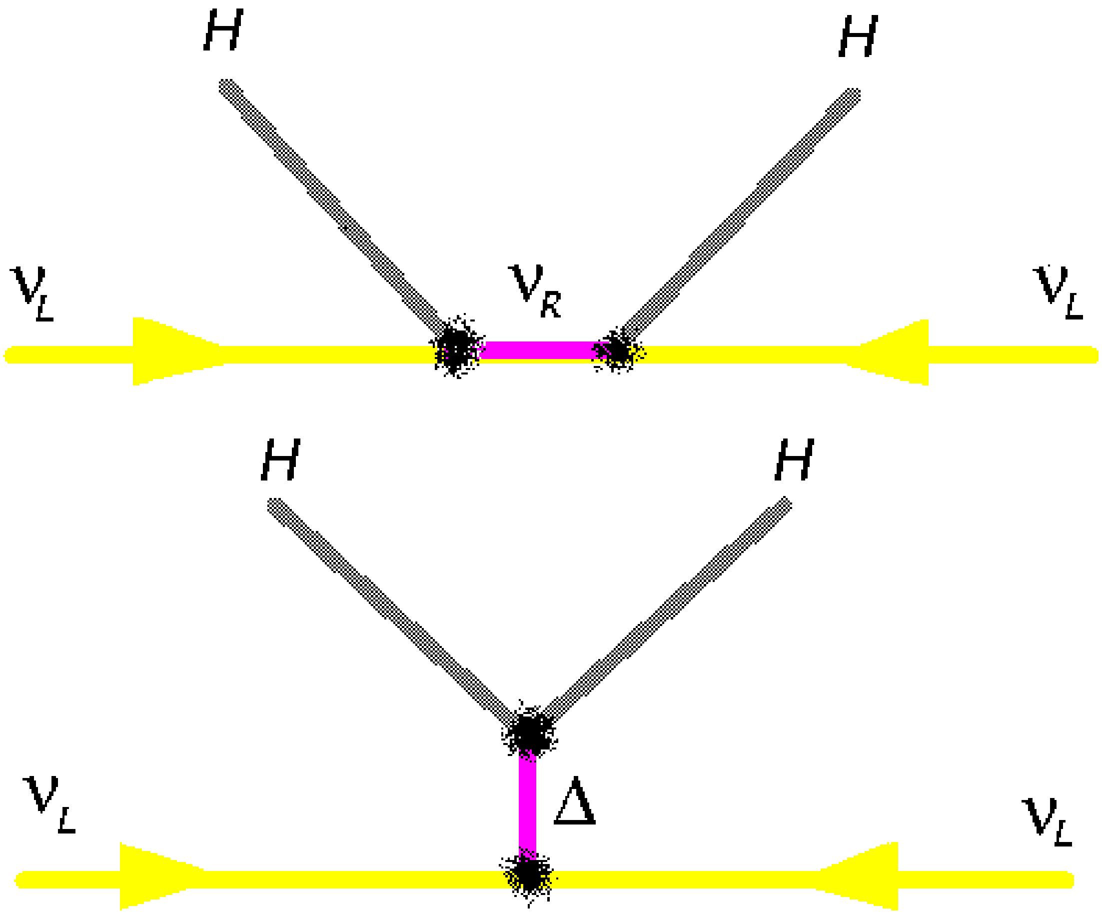

Spectrum with normal hierarchy: Dependence on $U_{e3}$
Experimental upper bound [2]
$M_{ee}$ [eV]
$m_1$ [eV]
1
0.1
0.01
0.001
0.0001
0.001
0.01
0.1
1


Spectrum with inverted hierarchy: Dependence on $U_{e3}$
Experimental upper bound [2]
$M_{ee}$ [eV]
$m_1$ [eV]
1
0.1
0.01
0.001
0.0001
0.001
0.01
0.1
1


1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$M_{ee}$ in eV
90%
99%
LMA
LOW
Normal
Inverted
$m_\nu$ = 1 eV


90% CL
$\Delta m^2_{23} < 0$
$\Delta m^2_{23} > 0$
$M_{ee}$ in eV
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
lightest neutrino mass in eV

In standard model, neutrino mass is zero.
But it is easy to extend the standard model to have neutrino masses! We recall just 2 mechanisms, based on right-handed neutrinos or $SU(2)_L$ triplets.

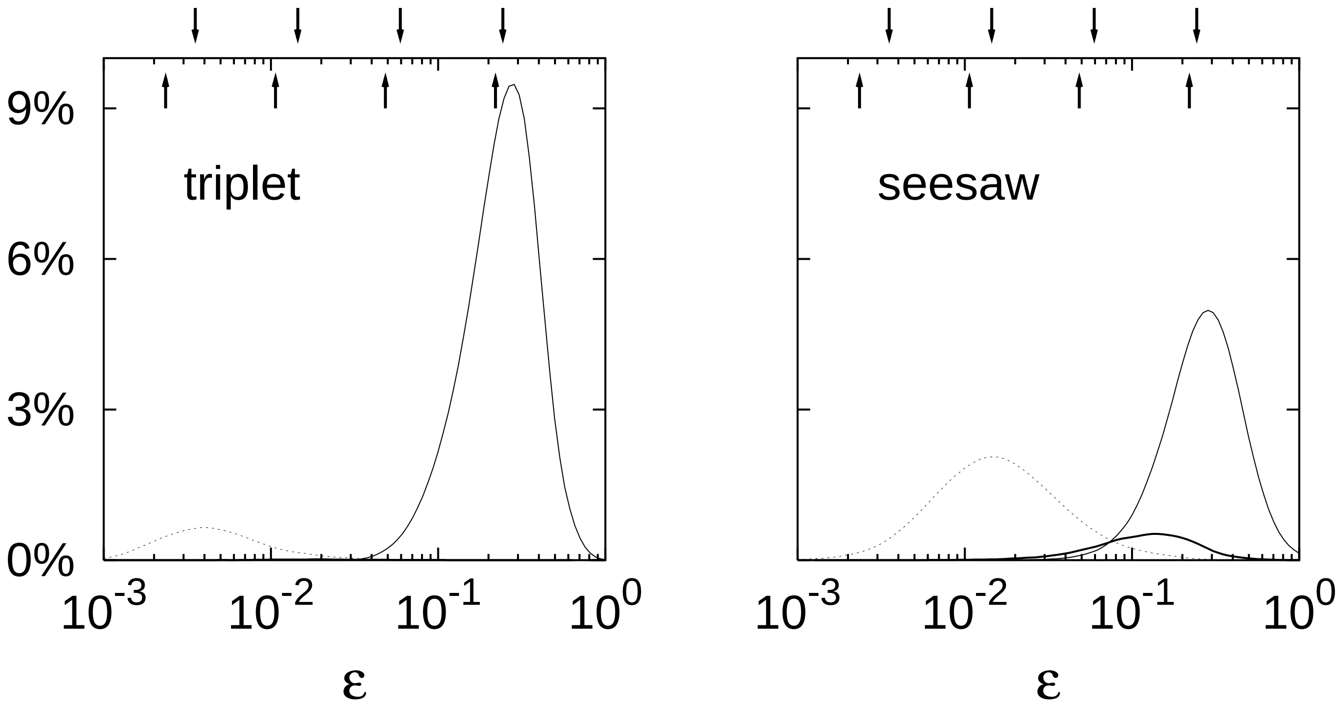



In both case, neutrino mass are small because the new fields are ultra-heavy (so called seesaw). First case looks "usual" because of yukawa couplings, but Majorana mass of $\nu_R$ is not "usual".

Maybe $\nu$ mass matrix is controlled by U(1) selection rules, e.g. $\nu_e$ has to pay one suppression factors—$\nu_\mu$ and $\nu_\tau$ do not:

$$\frac{\mathbf{M}}{m_0} \overset{\mathcal{O}(1)}{=} \begin{pmatrix} \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

This can be tested with available information on $\nu$'s, assuming that the $\mathcal{O}(1)$ factors are random numbers:




One can argue that $\varepsilon$ is a power of $\sin\theta_C$ (downward arrows), getting $\theta_{13}^2 \sim \mathbf{M}_{ee} \sim \sin\theta_C^n$ etc.

Note the case $\varepsilon = \sin\theta_C$, with LMA and big $\theta_{13}$ (dotted line is SMA, thick is LOW, thin is LMA)

Charged fermion masses known at $M_Z$; match'em with SO(10) at $M_{GUT}$ : back to $M_Z$; learn on $\nu$ masses.

Minimal SO(10) higgses have many uses:

- The singlet in **126** gives huge mass to $\nu^c$,
- its doublets help correct **10**-plet predictions on fermion masses (**10**-plet dominance OK for $3^{rd}$ generation).
- its triplet can contribute to neutrino mass

$2^{nd}$ and $3^{rd}$ generations at $M_{GUT}$ :

$$Y^{(10)} \approx \begin{pmatrix} 0.002 & 0 \\ 0 & 0.94 \end{pmatrix} \qquad \varepsilon\, Y^{(126)} \approx \begin{pmatrix} 0.014 & 0.027 \\ 0.027 & x \end{pmatrix}$$

If triplet dominates $\nu$ mass matrix, $\mathbf{M}_\nu \propto Y^{(126)} \Rightarrow$

$$\boxed{\theta_{23} \text{ can be large}}$$

$$\boxed{\text{weak mass hierarchies } m_2^2/m_3^2 \text{ favored}}$$

the larger $\theta_{23}$, the weaker the hierarchy

# Acknowledgment

*I wish to thank many peoples: the Organizers for kind support, my Collegues in the Gran Sasso Laboratory, and my Collaborators (spread out in the world) from whom I learned a lot.*

*But I feel I still I owe special thanks to B.Bajc, E.Bellotti, V.S.Berezinsky, C.Bucci, N.Ferrari, S.Pirro, A.Strumia, G.Senjanovic, A.Yu.Smirnov, V.I.Tretyak.*

*Most material I used is directly available on the net and most references can be easily found. But, I would like to add the reference to two papers alluded in the introduction, Sov.Phys.JETP 26:984,1968, and Phys.Lett.B26:630,1968, given to me by S.T.Petcov. The curious reader will find that some points I made in this talk are original.*

*I would greatly appreciate receiving your comments; my address is "vissani@lngs.infn.it".*