SNO RESULTS, MAJORANA NEUTRINOS, CP-VIOLATION, $(\beta\beta)_{0\nu}$ - DECAY

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NO-VE: NEUTRINO OSCILLATIONS IN VENICE

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hep/ph/0104218 to appear in PRD]

- $(\beta\beta)_{0\nu}$ - decay and the effective Majorana mass
- The 3-ν mixing case: i) predictions of $|\langle m \rangle|$ in the hierarchical, inverted hierarchy and mass degeneracy spectra
  ii) information on m_1 from $|\langle m \rangle|$
  iii) information on CPV from $|\langle m \rangle|$
- The 4-ν mixing case: predictions of $|\langle m \rangle|$ in the 2+2A, 2+2B, 3+1A, 3+1B, 3+1C neutrino mass spectra.
- Conclusions

References:

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- Strong indications of NEUTRINO OSCILLATIONS (from atmospheric, solar-ν data).

⬇

If confirmed, they would imply the EXISTENCE OF

$$\boxed{\begin{array}{c}\text{NEUTRINO MIXING}\\ \text{and}\\ \text{MASSIVE NEUTRINOS.}\end{array}}$$

- Then the foundamental question to address would b

the **NATURE** OF **NEUTRINOS**:

DIRAC PARTICLES in theories with L conserved	**?**	MAJORANA PARTICLES in theories with L violated

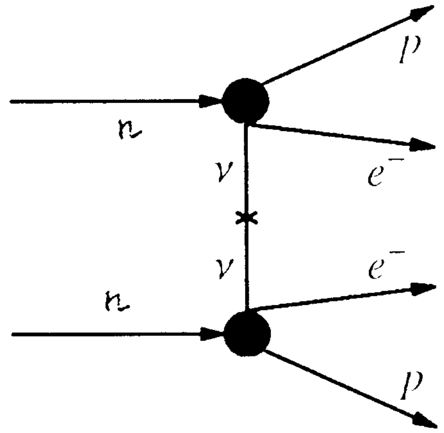
- The question of massive neutrinos is one of the foundamental questions related to the problem of ν-mixing
- The nature of massive neutrinos is related to the symmetries of elementary particle interactions.
- The Majorana nature of neutrinos can manifest itself in $\Delta L = 2$ processes. Now the most sensitive one is $(\beta\beta)_{0\nu}$ - decay .

NEUTRINOLESS DOUBLE β-DECAY

$$(A, Z) \longrightarrow (A, Z+2) + e^- + e^-$$

$\Delta L = 2$

Majorana neutrinos



The probability amplitude is sensitive to the EFFECTIVE MAJORANA MASS PARAMETER $|\langle m \rangle|$:

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\alpha_{21}} + |U_{e3}|^2 m_3 e^{i\alpha_{31}} \right|$$

in the hypothesis of $3-\nu$ mixing.

- Experimentally $(\beta\beta)_{0\nu}$ not yet detected:

  $|\langle m \rangle| \lesssim (0.35 \div 1.05)$ eV (^{76}Ge Heidelberg-Moscow)

  $|\langle m \rangle| \lesssim (0.33 \div 1.35)$ eV (IGEX Collaboration)

- Higher sensitivity in the upcoming experiments:

  $|\langle m \rangle| \cong 0.1$ eV

  $|\langle m \rangle| \simeq 0.01$ eV

RELEVANT PARAMETERS IN $|\langle m \rangle|$

(3-ν mixing case)

- Oscillation parameters: i) $\Delta m^2_{\odot}$, Δm^2_{atm}

  ii) $\theta_{\odot}$, θ_{CHOOZ}

  They can be measured with good accuracy.
  θ_{atm} and δ do not play any role.

! **Crucial:** to determine the correct $\nu_{\odot}$-anomaly solution:

SNO	$\boxed{\text{LMA}}$	$tg^2\theta_{\odot} \simeq 0.2 \div 1.0$	$\Delta m^2_{\odot} \simeq 10^{-5} \div 10^{-4}\ eV^2$
	SMA	$tg^2\theta_{\odot} \simeq 10^{-4} \div 10^{-3}$	$\Delta m^2_{\odot} \simeq 10^{-9} \div 10^{-7}\ eV^2$
SNO	$\boxed{\text{LOW}}$	$tg^2\theta_{\odot} \simeq 0.4 \div 3.0$	$\Delta m^2_{\odot} \simeq 10^{-6} \div 10^{-5}\ eV^2$

- Non-oscillation parameters: i) m_1, mass of the lighest neutrino

  ii) α_{21}, α_{31}
  Majorana CPV phases
  If CP is conserved:
  $\alpha_{21}, \alpha_{31} = 0, \pm\pi$.

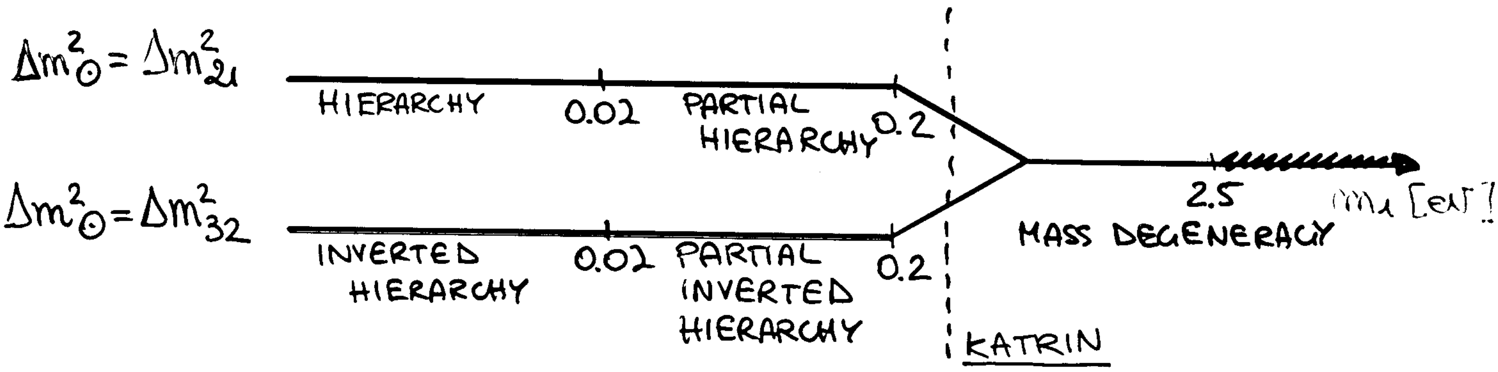
  These parameters are not constrained so far.
  ($m_1 \leq 2.2 \div 2.5$ eV from ^3H-β decay).

- Lightest ν mass m_1

m_1, $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$

All the 3 ν-masses are determined by and two mass-squared differences which have to be identified with $\Delta m^2_\odot$, Δm^2_{atm}:

$\Delta m^2_{atm} \equiv \Delta m^2_{31}$ $\qquad$ $\Delta m^2_\odot = \Delta m^2_{21}, \Delta m^2_{32}$



! Crucial: to determine the correct mass spectrum fixing the value of m_1 and resolving the ambiguity $\Delta m^2_\odot = \Delta m^2_{21}, \Delta m^2_{32}$.

- CPV phases α_{21}, α_{31}

With mixing of 3 massive Majorana neutrinos, 3 CPV phases are relevant: δ, α_{21}, α_{31}.

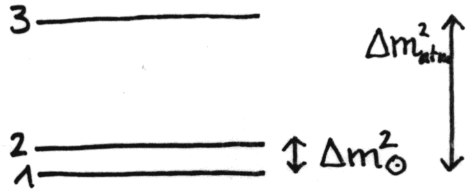
δ universal CPV phase. It does not enter in $(\beta\beta)_{0\nu}$-decay.

α_{21}, α_{31} Majorana CPV phases, they are present only if ν are Majorana particles. They enter in $(\beta\beta)_{0\nu}$-decay and other $\Delta L = 2$ processes. CP-conservation implies $\alpha_{21}, \alpha_{31} = 0, \pm\pi$.

HIERARCHICAL MASS SPECTRUM

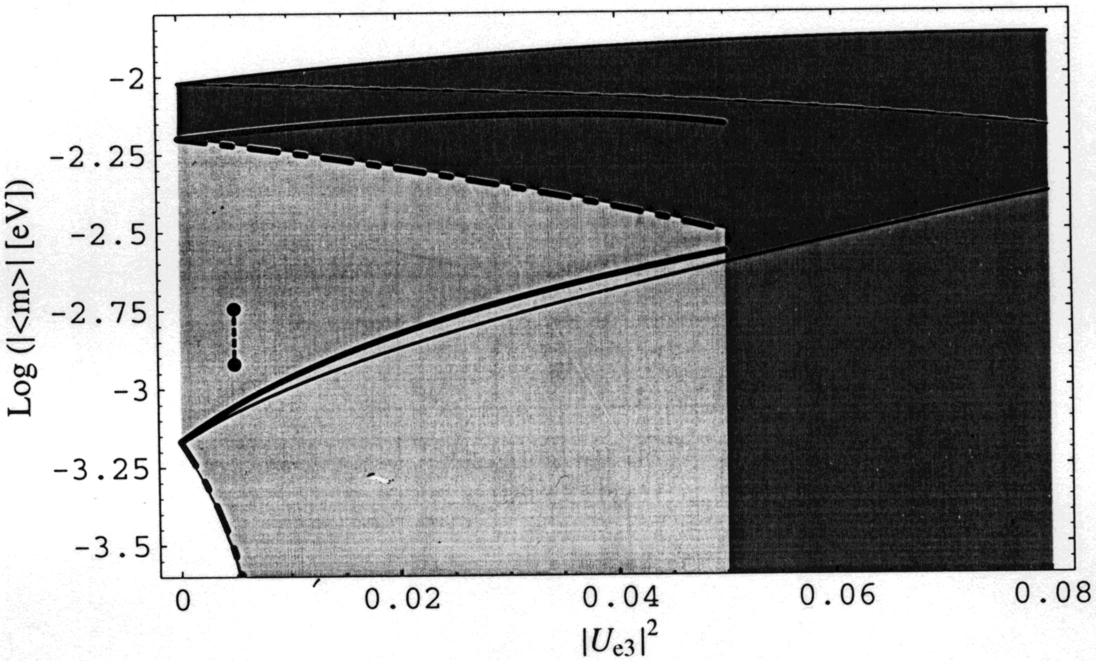
characterized by: $m_1 \ll m_2 \ll m_3$

$\Delta m^2_\odot = \Delta m^2_{21}$



$$|\langle m\rangle| = \left| \sqrt{\Delta m^2_\odot}\,(1-|U_{e3}|^2)\sin^2\theta_\odot + \sqrt{\Delta m^2_{atm}}\,|U_{e3}|^2 e^{i\alpha_{32}} \right|$$

Log(|<m>| [eV]) vs $|U_{e3}|^2$ in the LMA case:



$$(0 \div 0)\,\mathrm{eV} \leqslant |\langle m\rangle| \leqslant (7.6 \div 14)\times 10^{-3}\ \mathrm{eV}$$

- $|\langle m\rangle|$ can provide information on α_{32}
- however, being $|\langle m\rangle| \lesssim 0.01$ eV, $|\langle m\rangle|$ is beyond the sensitivity of the upcoming $(\beta\beta)_{0\nu}$-decay experiments.

INVERTED HIERARCHY SPECTRUM

characterized by: $m_1 \ll m_2 \simeq m_3$

$\Delta m^2_\odot = \Delta m^2_{32}$

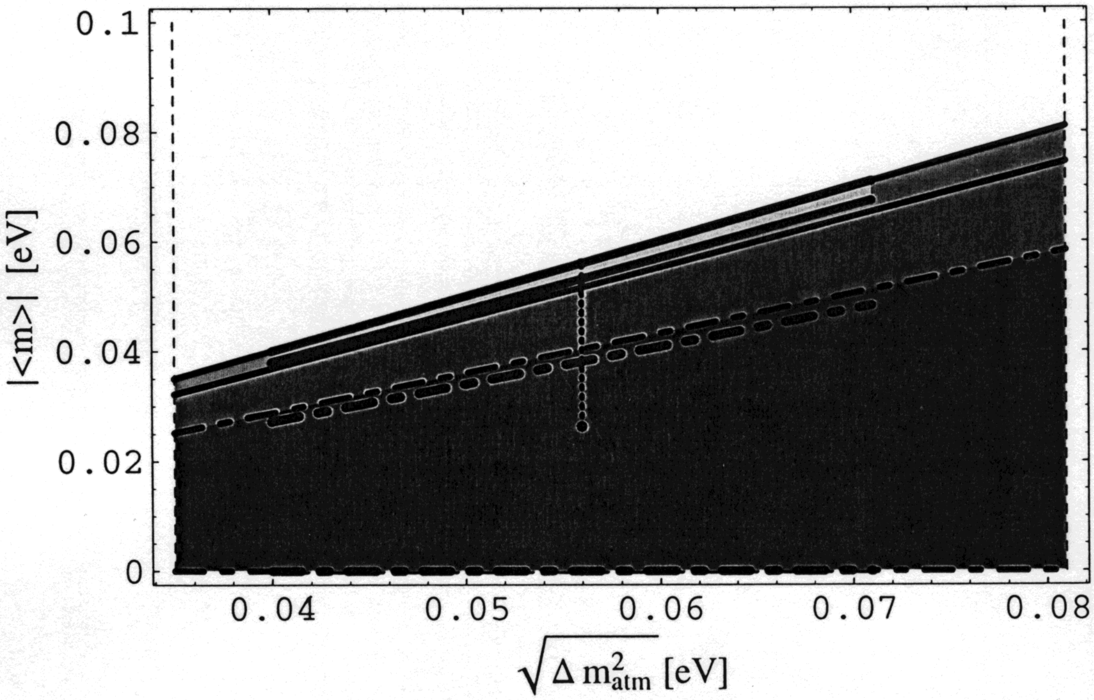
$\updownarrow \Delta m^2_\odot$

Δm^2_{atm}

$$|\langle m\rangle| = (1-|U_{e1}|^2)\sqrt{1-\sin^2 2\theta_\odot \sin^2\frac{\alpha_{32}}{2}}\ \sqrt{\Delta m^2_{atm}}$$

$|\langle m\rangle|$ can provide information on α_{32}.

$|\langle m\rangle|$ vs $\sqrt{\Delta m^2_{atm}}$ for the LMA MSW case:



$(7.3\times10^{-3} \div 0)\,eV \leq |\langle m\rangle| \leq (8.9 \div 8.1)\times 10^{-2}\,eV$

! $|\langle m\rangle|$ in the range of sensitivity of the upcoming $(\beta\beta)_{0\nu}$-decay experiments.

! The red colour denotes the **just CPV region** which can be spanned only in presence of CP violation.

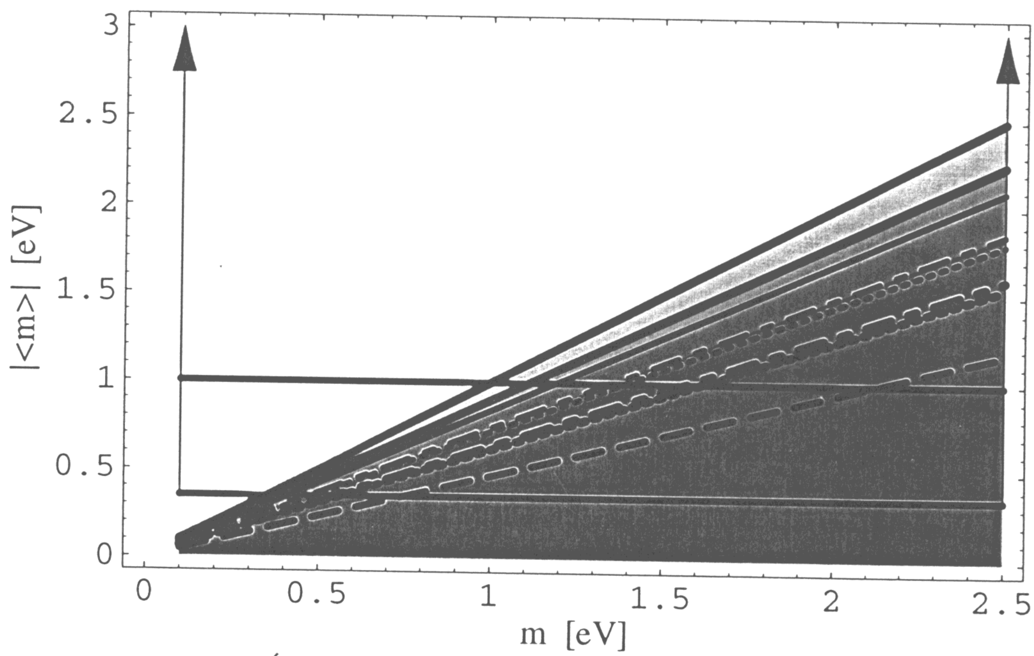
MASS QUASI-DEGENERACY

characterized by: $m_1 \simeq m_2 \simeq m_3 \equiv m$ 3, 2, 1 or 3, 2, 1

$$|\langle m\rangle| = m_1 \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot\, e^{i\alpha_{21}}\right)\left(1-|U_{e3}|^2\right) + |U_{e3}|^2 e^{i\alpha_{31}} \right|$$

$|\langle m\rangle|$ can provide information on m_1 and α_{21}, α_{31}.

$|\langle m\rangle|$ vs $m_1 \cong m$ for the LMA MSW case.



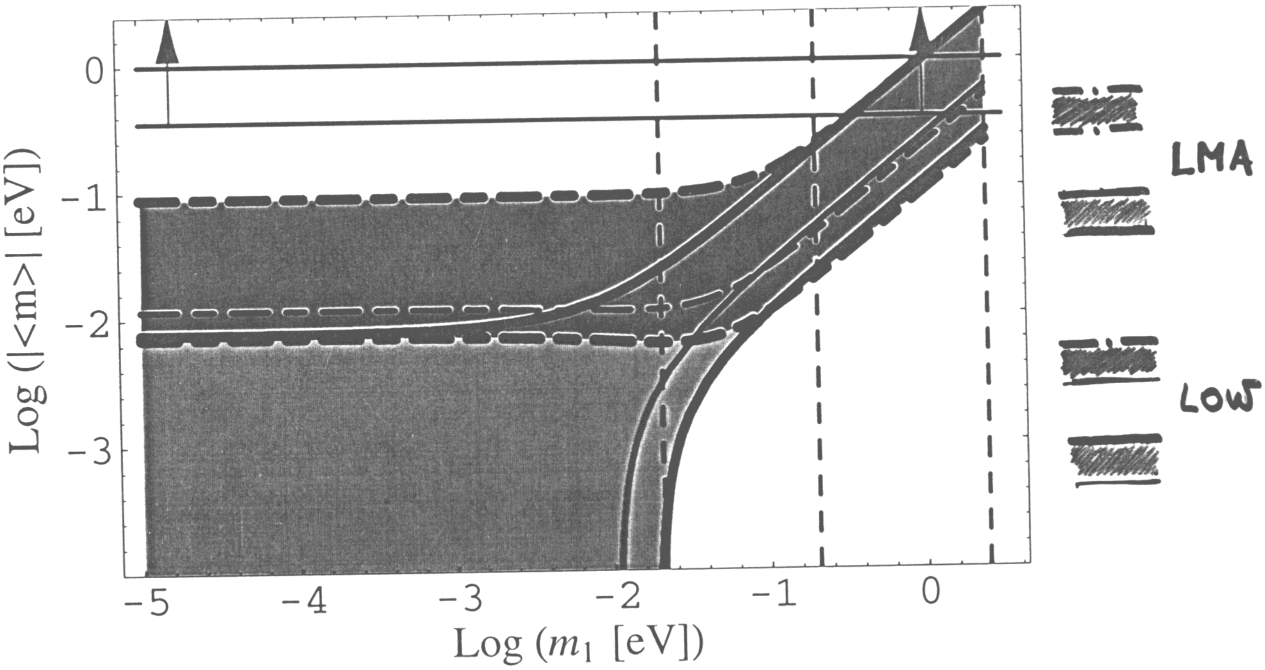
$0\,\mathrm{eV} \lesssim |\langle m\rangle| \lesssim 2.5\,\mathrm{eV}$

- part of the allowed range is already excluded by the Heidelberg-Moscow bound.

!
- most of the allowed region is in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$-decay experiments.

! The value of $|\langle m \rangle|$ can help to resolve the ambiguity $\Delta m^2_{\odot} = \Delta m^2_{21}$, Δm^2_{32} and to get information on m_1.

$\text{Log}(|\langle m \rangle|\ [eV])$ vs $\text{Log}(m_1\ [eV])$ for $\Delta m^2_{\odot} = \Delta m^2_{21}$ (green) and $\Delta m^2_{\odot} = \Delta m^2_{32}$ (blue):



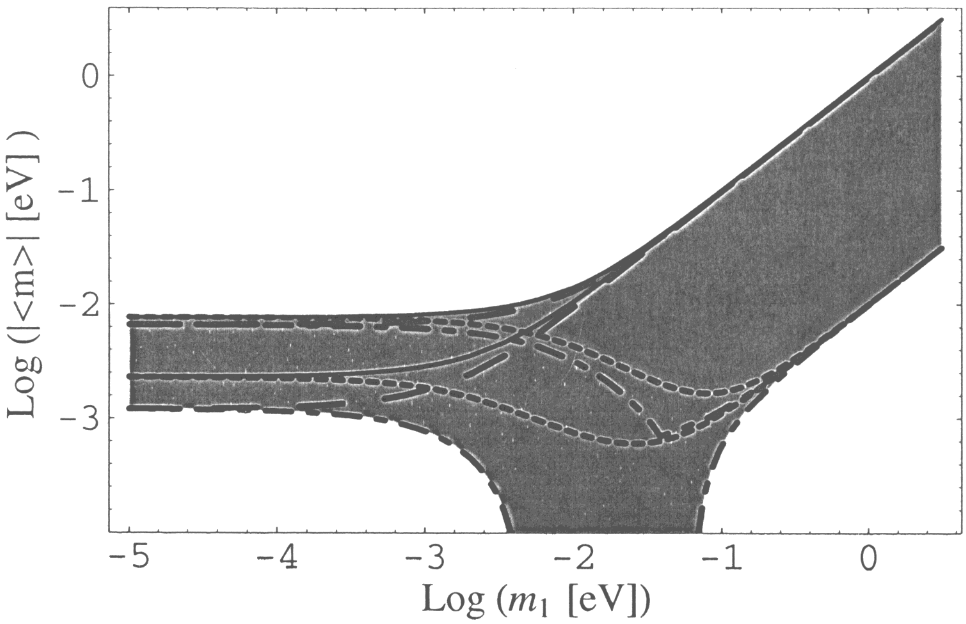
1) If $|\langle m \rangle| \gtrsim 0.01$ eV, the hierarchical spectrum is ruled out.

2) If $|\langle m \rangle| \gtrsim 0.1$ eV, the inverted hierarchical spectrum is disfavoured and the mass quasi-degeneracy case is favoured.

INFORMATION ON m_1

CASE A. $\Delta m^2_\odot \equiv \Delta m^2_{21}$

From the determination of the value of $|\langle m\rangle|$, we could get information on m_1 and CPV.



CP- parities:

+ + +

+ + −

+ − +

+ − −

Red: just CPV

$\cos 2\theta_\odot = 0$

$|U_{e3}|^2 = 0.01$

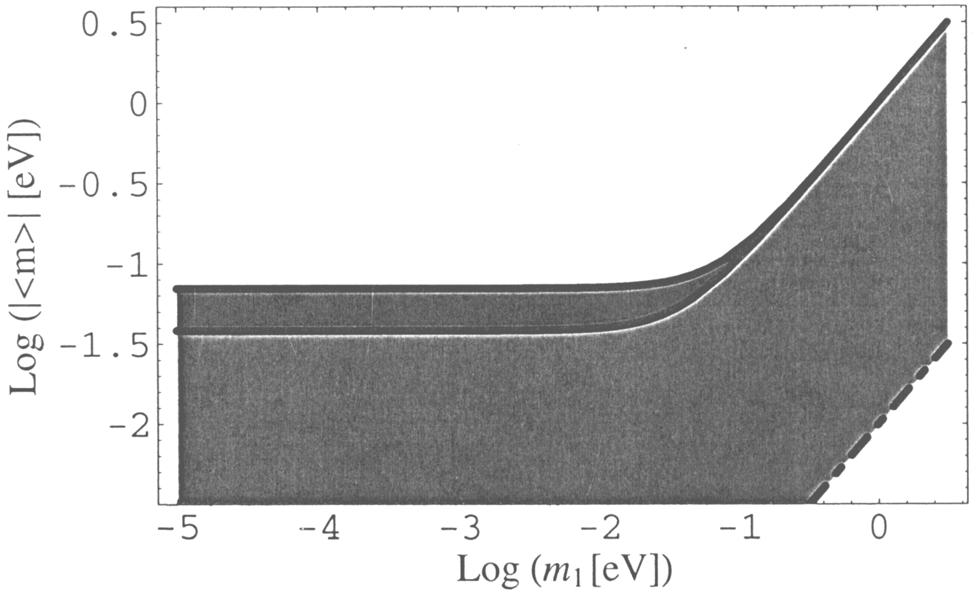
Log (|<m>| [eV]) vs Log (m_1 [eV]) for LMA.

i) If $|\langle m\rangle| > 10^{-2}$ eV, the value of m_1 is constrained in a range and in particular has a lower bound.

ii) If 10^{-3} eV $< |\langle m\rangle| < 10^{-2}$ eV, the value of m_1 has only an upper bound.

To infer information on CPV we need a constraint on m_1. From the values of m_1 (KATRIN) and $|\langle m\rangle|$ ($(\beta\beta)_{0\nu}$-decay) it will be possible to establish if CP-parity is violated in the leptonic sector through Majorana CPV phases.

CASE B $\Delta m^2_{\odot} = \Delta m^2_{32}$



$|U_{e1}|^2 = 0.01$

$\cos 2\theta_{\odot} = 0$ (LMA)

CP-parities:

$\pm + +$

$-\cdot-$ $\pm + -$

Red: just CPV

i) If $|\langle m\rangle| > 10^{-1}$ eV, m_1 is constrained to lie in a range of values and in particular has a lower bound. Only the $\pm + +$ CP-parities patterns are allowed and the value of m_1 is fixed (if CP conservation) or we have CP-violation.

ii) If $0.04\,\text{eV} < |\langle m\rangle| < 0.1\,\text{eV}$, m_1 has an upper limit from ^3H-β decay experiments.
Only the $\pm + +$ CP-parities patterns are allowed but m_1 is not constrained (CP-conservation) or CPV.

iii) If $|\langle m\rangle| < 0.04$ eV, m_1 has only an upper bound. In the case of CP conservation only the $\pm + -$ CP-parity patterns are allowed with fixed value of m_1.
If $m_1 < 0.5$ eV and $|\langle m\rangle| > 0.005$ eV, then
! we have CP-violation.

INFORMATION ON CP-VIOLATION

From a measurement of $|\langle m \rangle|$, it might be possible to get information on the CPV phases: α_{21}, α_{31}.
It depends on:

i) the solution of the solar-ν problem:

- for the LMA (LOW) solution, currently favoured, it will be possible to constrain at least one of the CPV phases.
- for the SMA solution, it will be very difficult to get any information on α_{21} and α_{31} as the dependence of $|\langle m \rangle|$ on them is suppressed by the values of the mixing angles.

ii) the spectrum considered:

- $\Delta m^2_{\odot} = \Delta m^2_{21}$, m_1 negligible:
  $|\langle m \rangle|$ is beyond the sensitivity of present and upcoming experiments.

- $\Delta m^2_{\odot} = \Delta m^2_{32}$, m_1 negligible:
  $|\langle m \rangle|$ can fix the value of $\alpha_{31} - \alpha_{21}$.

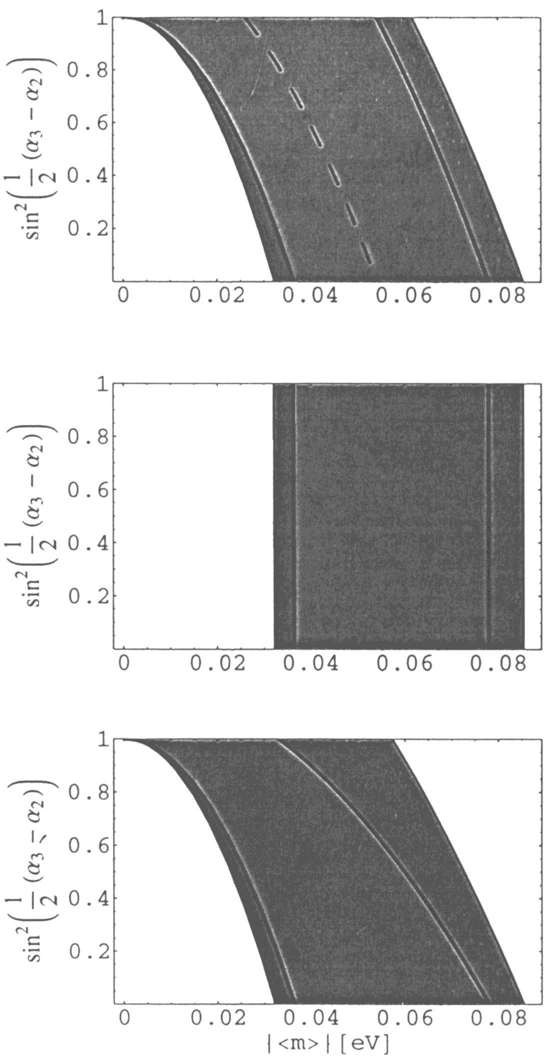
- $\Delta m^2_{\odot} = \Delta m^2_{32}, \Delta m^2_{21}$, $m_1 > 0.2\,eV$:
  $|\langle m \rangle|$ can constrain α_{21} and α_{31}.

$\Delta m^2_\odot = \Delta m^2_{32}$, m_1 negligible

From the measurement of $|\langle m \rangle|$, it might be possible to infer the value of the CPV phase α_{32} :

$$\sin^2 \frac{\alpha_{32}}{2} = \left(1 - \frac{|\langle m \rangle|^2}{\Delta m^2_{atm} \left(1 - |U_{e1}|^2\right)} \right) \frac{1}{\sin^2 2\theta_\odot}$$

(S. Bilenky et al '96)



LMA

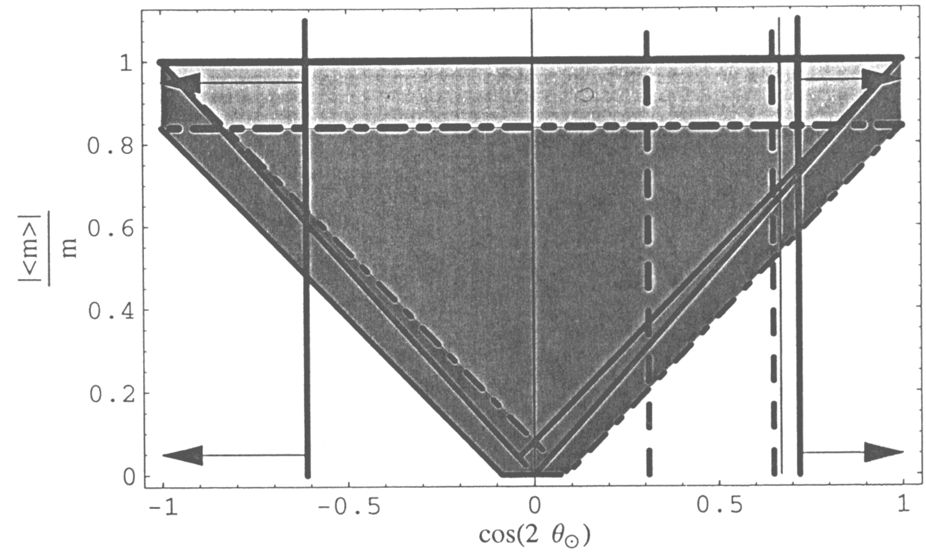
SMA

LOW

$\sin^2 \frac{\alpha_{32}}{2}$ vs $|\langle m \rangle|$ according to the different solutions of the $\nu_\odot$ - problem.

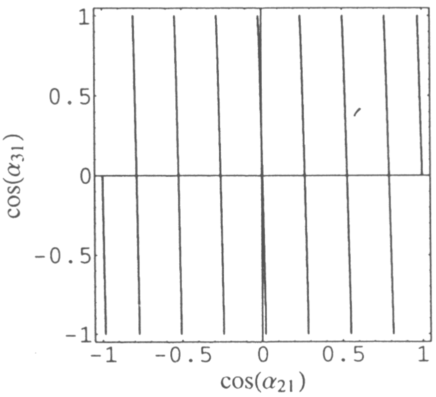
In the case of the SMA solution, we have no constraints on α_{32}

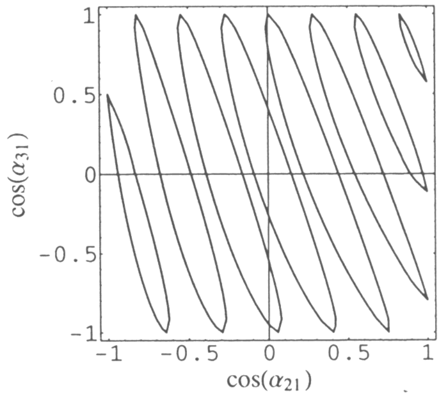
$\Delta m^2_{\odot} = \Delta m^2_{21}, \Delta m^2_{31}$, $m_1 > 0.2\,eV$



The red colour denotes the just CPV region.
Two CPV phases are relevant : α_{21} and α_{31}.

If $|\langle m\rangle|$ is determined, we cannot fix the values of both phases but we can constrain their ranges. We plot $\cos\alpha_{31}$ vs $\cos\alpha_{21}$ for fixed values of the parameters and different values of $|\langle m\rangle|/m$.





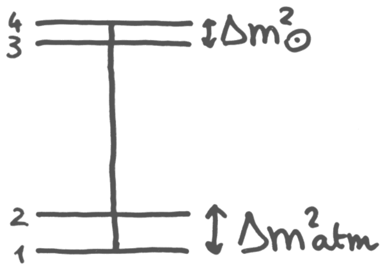
$$\frac{|\langle m\rangle|^2}{m^2} - \left(\cos^4\theta_{\odot}(1-|U_{e3}|^2)^2 + \sin^2\theta_{\odot}(1-|U_{e3}|^2)^2 + |U_{e3}|^4\right)$$
$$= 2\cos^2\theta_{\odot}\,|U_{e3}|^2(1-|U_{e3}|^2)\cos\alpha_{31} + 2\sin^2\theta_{\odot}\cos^2\theta_{\odot}(1-|U_{e3}|^2)^2\cos\alpha_{21}$$
$$+ 2\sin^2\theta_{\odot}\,|U_{e3}|^2(1-|U_{e3}|^2)\cos(\alpha_{21}-\alpha_{31})$$

$|\langle m \rangle|$ IN THE 4-ν MIXING CASE

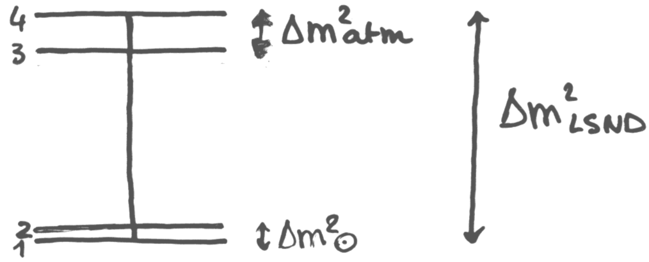
If LSND results will be confirmed, then to explain atmospheric, solar and LSND results in terms of oscillations we need to consider the mixing of 4 neutrinos.

The predictions on $|\langle m \rangle|$, using the oscillations parameters and varying freely the non-oscillation ones m_1, α_{21}, α_{31}, α_{41} depend strongly on the spectrum considered.

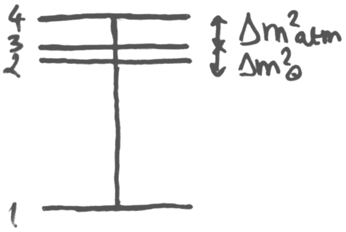
We consider the following possibilities:



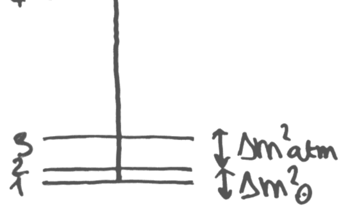
2+2A



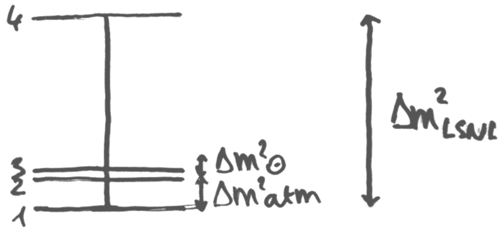
2+2B



3+1A

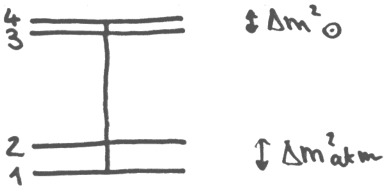


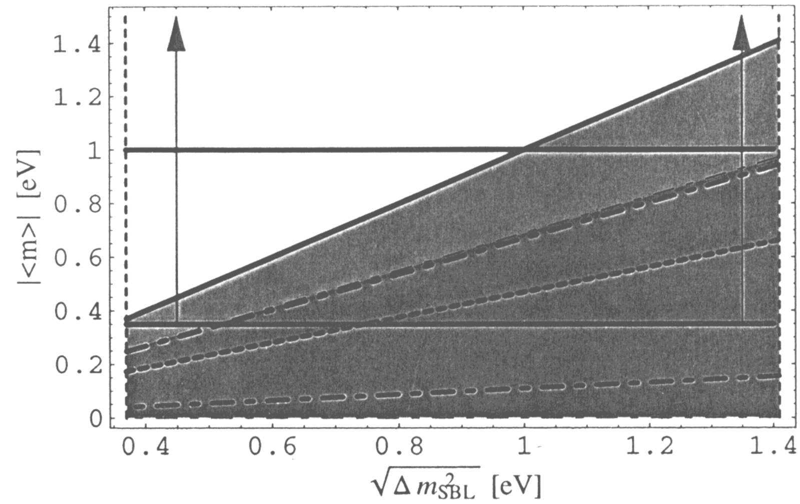
3+1B



3+1C

2+2A



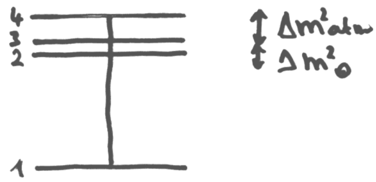


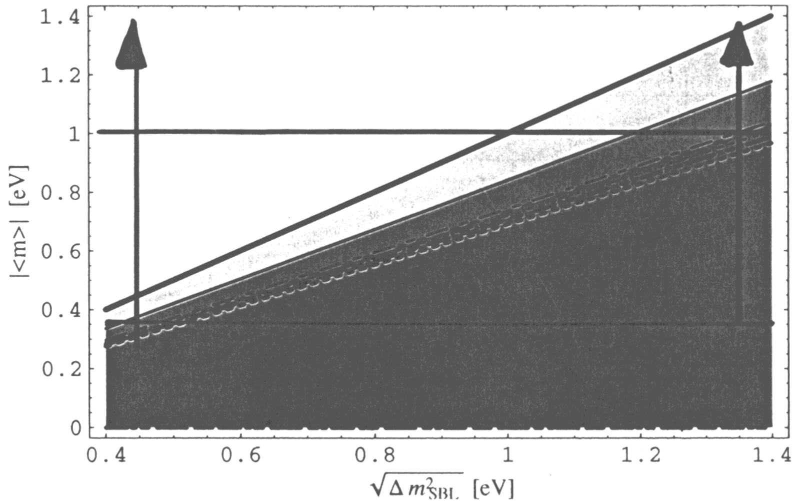
(LMA)

$m_\beta = \sqrt{m_1^2 + \Delta m^2_{SBL}} \gtrsim 0.4\,e$

completely tested by KATRIN

3+1A



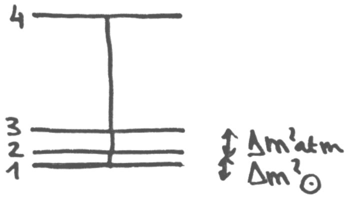


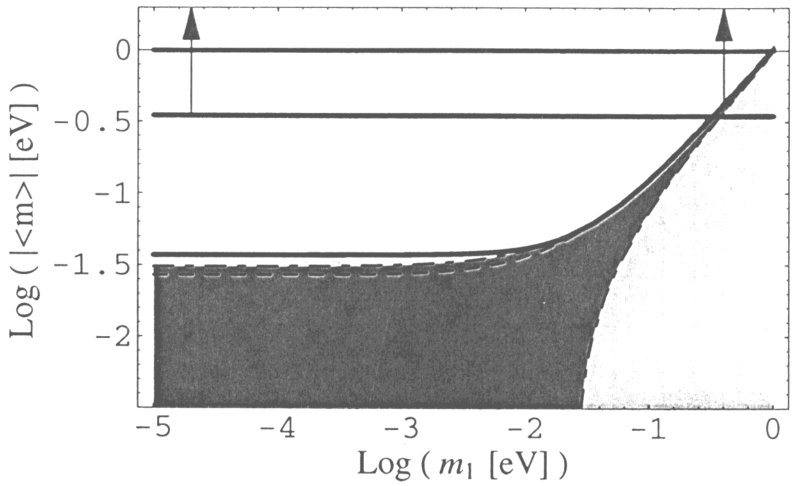
(LMA)

In both cases, most of the range of $|\langle m \rangle|$ is in the region of sensitivity of present and upcoming experiments.

The lower bound on $|\langle m \rangle|$ depends strongly on $\cos 2\theta_\odot$.

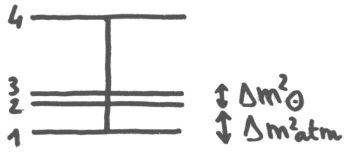
3+1 B

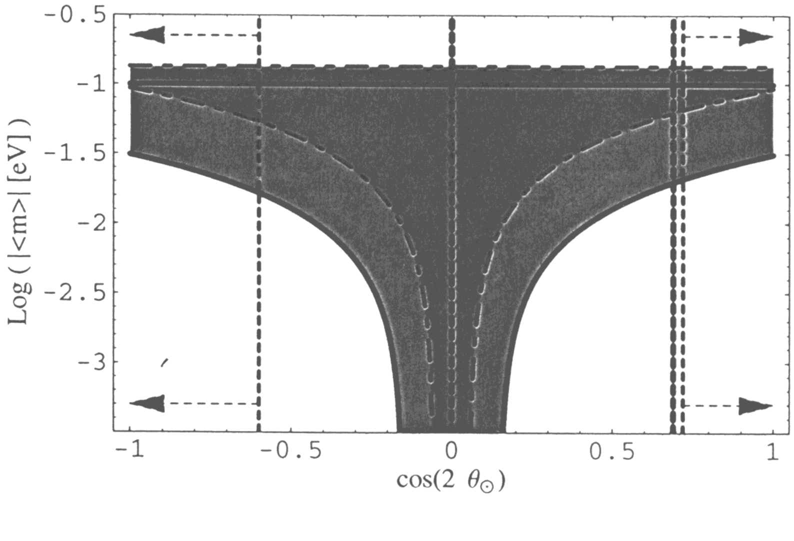




Blue: SMA
Yellow + Blue: LMA, LOW.

3+1 C

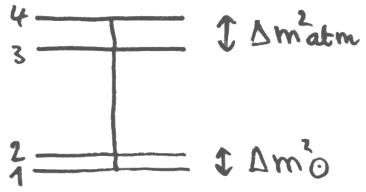


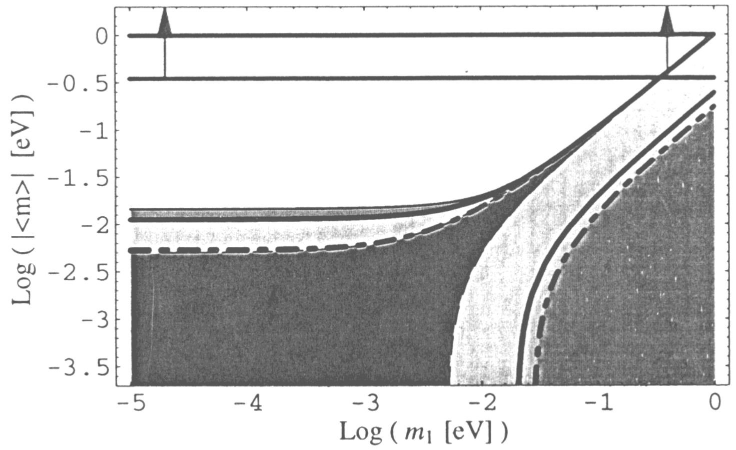


(LMA)

Unless $m_1 \gtrsim 0.1$ eV, $|\langle m \rangle|$ is much lower than in the two previous cases and only upcoming experiments will be sensitive to its value.

2+2B

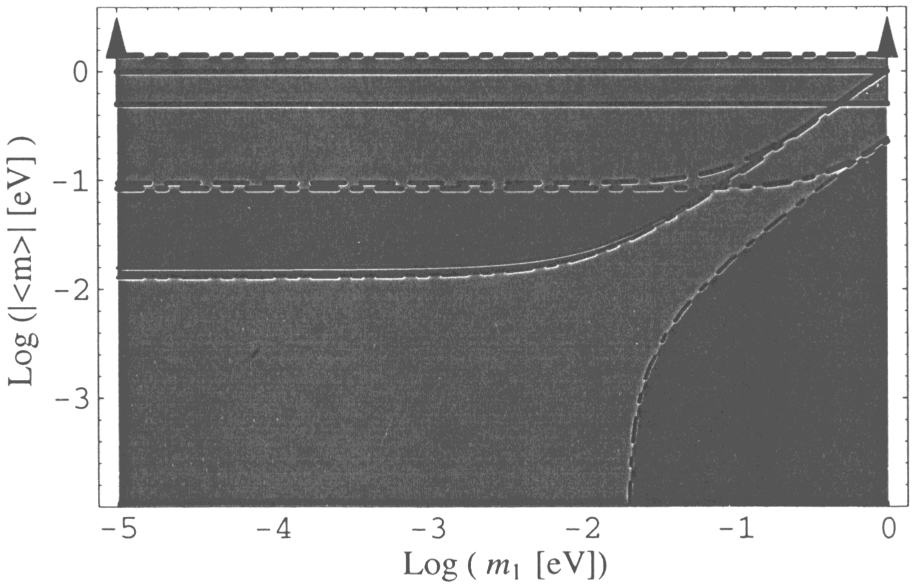




Blue: SMA
Yellow + Blue: LMA, LOW

Unless $m_1 \gtrsim 0.1$ eV, $|\langle m\rangle| < 0.02$ eV, far beyond the sensitivity of upcoming experiments.

We can summarize the predictions on $|\langle m\rangle|$ as:



If $|\langle m\rangle| > 0.1$ eV, the allowed spectra are 2+2A and 3+1A while the 2+2B, 3+1B and 3+1C are ruled out.
If $|\langle m\rangle| < 0.1$ eV, the 2+2A spectrum is disfavoured.

CONCLUSIONS

> If $(\beta\beta)_{0\nu}$-decay is detected, then we could conclude that neutrinos are **massive Majorana** particles and the total lepton charge **L** is not conserved ($\Delta L = 2$).

- 3-ν MIXING CASE

With an improvement of the precision of the oscillation parameters, $\Delta m^2_{\odot}$, Δm^2_{atm}, $\theta_{\odot}$, θ_{CHOOZ}, the determination of the value of $|\langle m \rangle| \gtrsim 0.01$ eV would lead to obtain information on m_1 and then on the type of mass spectrum.
In particular, in the 3-ν mixing case:

i) for the LMA and LOW solutions of the $\nu_{\odot}$-anomaly, we could obtain either a range for m_1 (if $\Delta m^2_{\odot} = \Delta m^2_{21}$ or $\Delta m^2_{\odot} = \Delta m^2_{32}$, $m_1 > 10^{-2}$ eV), or an upper bound on m_1 (if $\Delta m^2_{\odot} = \Delta m^2_{32}$, $m_1 < 10^{-2}$ eV).
With additional information on m_1 (KATRIN) we could establish CPV in the lepton sector and either the value of CPV phases α_{21}, α_{31} (if CPV) or the CP-parity patterns of the ν (if CPC).
(*) where are
(Exceptional cases where $|\langle m \rangle|$ alone $\Rightarrow$ CPV).

ii) for the SMA solution, we could obtain either the value of m_1 ($\Delta m^2_{\odot} = \Delta m^2_{21}$ or $\Delta m^2_{32} = \Delta m^2_{\odot}$, $m_1 > 10^{-2}$ eV) or an upper bound on m_1 ($\Delta m^2_{\odot} = \Delta m^2_{32}$, $m_1 < 10^{-2}$ eV).
No information on CP can be inferred.

- $4-\nu$ MIXING CASE

The LSND results will be tested within the next few years by the MiniBooNE experiment.

For 4 of the allowed spectra (2+2A, 3+1A, 3+1B, 3+1C), large parts of the ranges of $|\langle m \rangle|$ are in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$ experiments.
The 2+2A and 3+1A spectra can be completely tested by the KATRIN experiments.
For the 2+2B spectrum, $|\langle m \rangle|$ is beyond the sensitivity of the upcoming experiments.