

WHAT WE (WOULD LIKE TO) KNOW ABOUT THE NEUTRINO MASS

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ABSTRACT

We present updated values for the mass-mixing parameters relevant to neutrino oscillations, with particular attention to emerging hints in favor of $\theta_{13} > 0$. We also discuss the status of absolute neutrino mass observables, and a possible approach to constrain theoretical uncertainties in neutrinoless double beta decay. Desiderata for all these issues are also briefly mentioned.

1. Neutrino oscillation parameters and hints of $\theta_{13} > 0$

In the last decade, a series of beautiful ν oscillation experiments, interpreted within a theoretical framework with three massive and mixed neutrinos, has provided stringent constraints on the ν mass-squared differences (δm^2 , Δm^2) and mixing angles ($\sin^2 \theta_{12}$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$)—see ¹⁾ for notation and conventions. Desiderata include the sign of Δm^2 (i.e., the ν mass spectrum hierarchy), a possible CP-violating phase δ , and a lower bound (if any) on the smallest ν mixing angle θ_{13} .

At this NO-VE Workshop, we have presented recent progress on the latter issue, by showing how the combination of recent solar and long-baseline reactor (KamLAND) data leads to a slight preference for $\sin^2 \theta_{13} \sim 10^{-2}$. More precisely, using solar ν data *prior* to the Neutrino 2008 Conference ²⁾, we have noted that the slight difference between the value of $\sin^2 \theta_{12}$ preferred by such data, as compared with the one preferred by KamLAND data, can be significantly reduced for $\theta_{13} > 0$ —see the panels in Fig. 1. This reduction, originating from different functional forms of the survival probability $P_{\nu_e \rightarrow \nu_e}(\sin^2 \theta_{12}, \sin^2 \theta_{13})$ in the two classes of experiments, led to a slight preference for $\theta_{13} > 0$ (at the level of $\sim 0.5\sigma$). An older, independent preference for $\theta_{13} > 0$ from atmospheric neutrino data had already been found in ¹⁾ (at the level of $\sim 0.9\sigma$). Added together, these hints provided a 1σ indication in favor of $\theta_{13} > 0$: $\sin^2 \theta_{13} \simeq 0.01 \pm 0.01$, as presented at this Workshop using available data. We then remarked that new solar ν data could potentially corroborate such indication.

After Neutrino 2008 ²⁾, we have performed a follow-up global analysis with the latest (SNO-III) solar neutrino results ³⁾. The analysis has indeed sharpened such intriguing indication, which now reaches an interesting C.L. of $\sim 90\%$ (i.e., $\sim 1.6\sigma$):

$$\sin^2 \theta_{13} \simeq 0.016 \pm 0.010 . \quad (1)$$

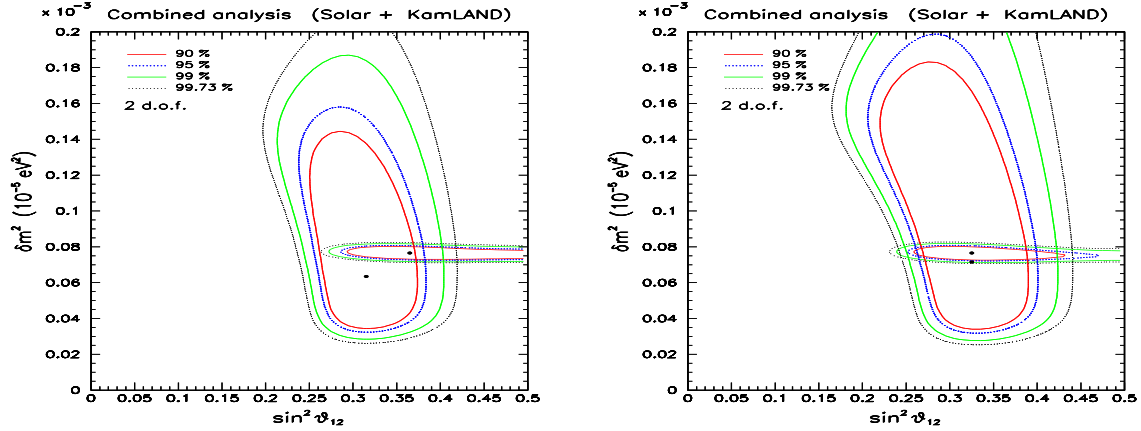


Figure 1: Comparison of regions allowed by KamLAND data (2008) and by solar ν data (prior to Neutrino 2008), according to our analysis. Contours refer to two dof. Black dots represent best-fit points. The left panel refers to $\sin^2 \theta_{13} = 0$ (fixed); note the slight distance between the best-fit points. The right panel refers to $\sin^2 \theta_{13} = 0.03$ (fixed); the best-fit points are closer, although the overall goodness of the fit (not reported here) is slightly worsened.

Figure 2 (left panel) shows the regions separately allowed at 1σ ($\Delta\chi^2 = 1$, dotted) and 2σ ($\Delta\chi^2 = 4$, solid) from the analysis of solar (S) and KamLAND (K) neutrino data, in the plane spanned by $(\sin^2 \theta_{12}, \sin^2 \theta_{13})$. These parameters are positively and negatively correlated in the S and K regions, respectively, as a result of different functional forms for $P_{ee}(\sin^2 \theta_{12}, \sin^2 \theta_{13})$ in the two cases. The S and K allowed regions, which do not overlap at 1σ for $\sin^2 \theta_{13} = 0$, merge for $\sin^2 \theta_{13} \sim \text{few} \times 10^{-2}$. The best fit (dot) and error ellipses (in black) for the S+K combination are shown in the middle panel of Fig. 2; a hint of $\theta_{13} > 0$ emerges at $\sim 1.2\sigma$ level. Finally, the independent ($\sim 0.9\sigma$) hint of $\theta_{13} > 0$ from the combination of atmospheric, LBL accelerator, and CHOOZ data reinforces the overall preference for $\theta_{13} > 0$, which emerges at the overall level of $\sim 1.6\sigma$ in the right panel of Fig. 2 (all data).

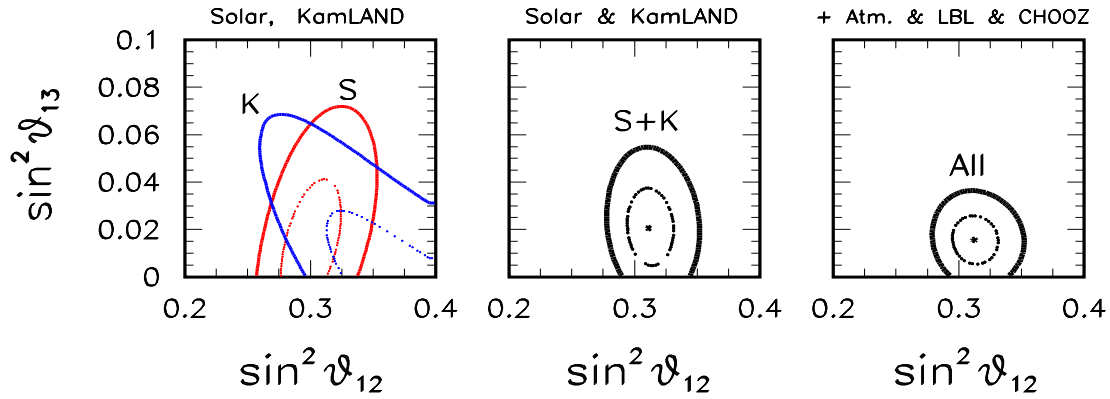


Figure 2: Analysis after Neutrino 2008: Contours of the regions allowed at 1σ (dotted) and 2σ (solid) in the plane $(\sin^2 \theta_{12}, \sin^2 \theta_{13})$. Left and middle panels: solar (S) and KamLAND (K) data, both separately (left) and in combination (middle). Right panel: All data. Taken from Ref. ³⁾.

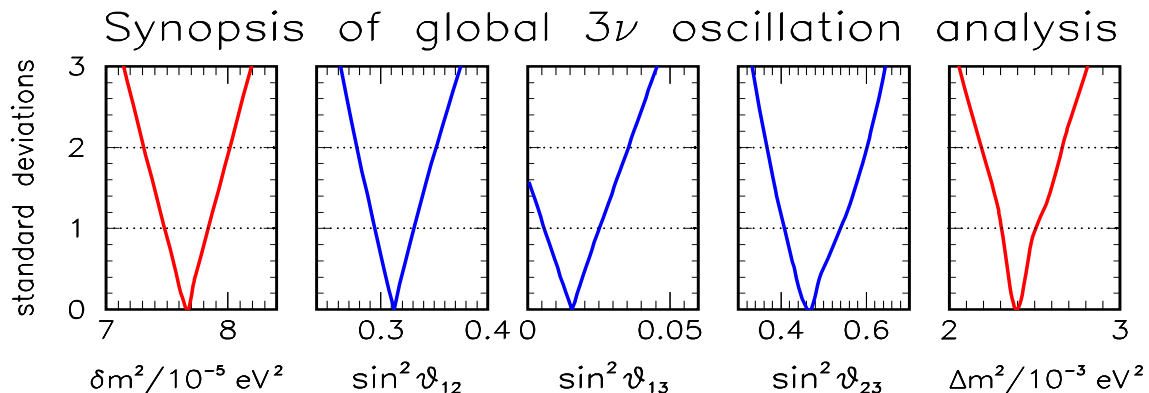


Figure 3: Global analysis after Neutrino 2008, from Ref. ⁴⁾: Bounds on the mass-mixing oscillation parameters, in terms of standard deviations from the best fit. Note again the 1.6σ preference for $\theta_{13} > 0$. Desiderata include a possible confirmation of such preference in future reactor and accelerator oscillation searches.

At this Workshop we also updated the estimates of all the mass-mixing parameters. Here we present the latest results including Neutrino 2008 data ⁴⁾. Figure 3 displays a synopsis of the ν parameters, in terms of standard deviations n_σ from the best fit ($n_\sigma = \sqrt{\Delta\chi^2}$ after χ^2 marginalization). Table 1 summarizes the numerical ranges. Note that in the discussion of Sec. 2 we shall show results at a conservative 2σ (95%) C.L., in which case only an upper bound can be placed on θ_{13} .

Table 1: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges, from Ref. ⁴⁾.

Parameter	$\delta m^2/10^{-5} \text{ eV}^2$	$\sin^2 \theta_{12}$	$\sin^2 \theta_{13}$	$\sin^2 \theta_{23}$	$\Delta m^2/10^{-3} \text{ eV}^2$
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

2. Status of absolute neutrino mass observables

The three main observables sensitive to absolute ν masses are: the effective mass m_β in single beta decay, the effective Majorana mass $m_{\beta\beta}$ in neutrinoless double beta ($0\nu 2\beta$) decay, and the sum of ν masses Σ in cosmology—see Ref. ¹⁾ for notation. Desiderata include an undisputed nonzero signal for at least one such quantity.

2.1. $0\nu 2\beta$ decay updates

The final analysis of part of the Heidelberg-Moscow (HM) Collaboration reports a $0\nu 2\beta$ signal in ^{76}Ge with half-life $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ y}$ (1σ errors) at a claimed C.L. $> 6\sigma$. Desiderata include an independent check of this claim in a different experiment.

Using generous uncertainties for the $0\nu 2\beta$ nuclear matrix elements (NME) we find

$$\log(m_{\beta\beta}/\text{eV}) = -0.54 \pm 0.26 \quad (\text{HM claim, } 2\sigma) . \quad (2)$$

The Cuoricino experiment does not find $0\nu 2\beta$ decay signals in ^{130}Te and quotes $T_{1/2}^{0\nu} > 2.5 \times 10^{24}$ y at 95% C.L. Using the latter limit as $\log(T_{1/2}^{0\nu}/\text{y}) > 24.4$, we get

$$\log(m_{\beta\beta}/\text{eV}) < [-0.63, -0.07] \quad (\text{Cuoricino, } 2\sigma) , \quad (3)$$

where the range due to the 2σ uncertainty of the NME is explicitly reported.

A comparison of the corresponding $m_{\beta\beta}$ ranges (2σ),

$$0.16 < m_{\beta\beta}/\text{eV} < 0.52 \quad (\text{HM claim}) , \quad (4)$$

$$0 \leq m_{\beta\beta}/\text{eV} < 0.23 \quad (\text{Cuoricino, “favorable” NME}) , \quad (5)$$

$$0 \leq m_{\beta\beta}/\text{eV} < 0.85 \quad (\text{Cuoricino, “unfavorable” NME}) , \quad (6)$$

shows that current Cuoricino data may or may not disfavor a fraction of the HM range for $m_{\beta\beta}$ at 2σ , depending on the (still quite uncertain) value of the ^{130}Te $0\nu 2\beta$ NME. Desiderata include a reduction of the NME uncertainties (see also Sec. 3). Therefore, the $0\nu 2\beta$ claim remains an open issue at present, and we shall consider the possibility that it corresponds to a real signal. See Ref. ⁴⁾ and references therein for details about the above limits.

2.2. Cosmology updates

In Ref. ⁴⁾, in collaboration with A. Melchiorri, P. Serra, J. Silk, and A. Slosar, we have also updated the constraints on Σ including WMAP 5-year and other data. We consider four representative combinations of cosmological data, which lead to increasingly stronger upper limits on Σ : (1) CMB anisotropy data from: WMAP 5y, ACBAR, VSA, CBI, and BOOMERANG; (2) the above CMB results plus the HST prior on the value of the reduced Hubble constant, and the luminosity distance SN-Ia data; (3) The data in (2) plus BAO data; (4) all the previous data, plus $\text{Ly}\alpha$ forest clouds data. The corresponding upper limits on Σ are summarized in Table 2. We shall focus on the two extreme cases 1 and 4.

Table 2: Cosmological datasets and corresponding 2σ bounds on $\Sigma = m_1 + m_2 + m_3$.

Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + HST + SN-Ia	< 0.75 eV
3	CMB + HST + SN-Ia + BAO	< 0.60 eV
4	CMB + HST + SN-Ia + BAO + $\text{Ly}\alpha$	< 0.19 eV

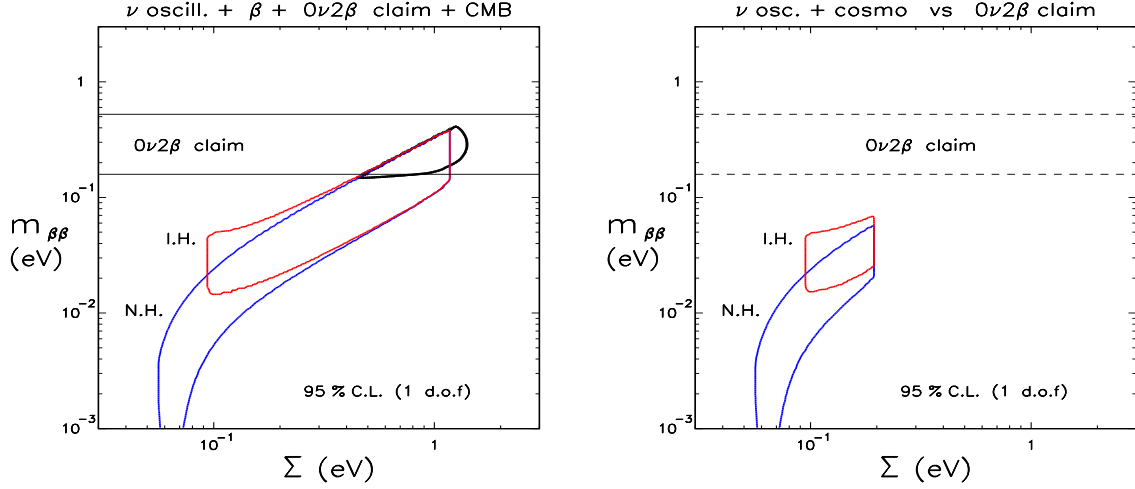


Figure 4: Comparison on bounds placed by oscillation data (slanted bands, for normal and inverted hierarchy), cosmological data (vertical limits) and the $0\nu 2\beta$ claim (horizontal band), in the plane $(\Sigma, m_{\beta\beta})$. Left panel: Global combination of oscillation plus CMB data (case 1 in Table 2) with the $0\nu 2\beta$ decay claim. Right panel: Bounds from oscillation plus all cosmological data (case 4 in Table 2), contrasted with the $0\nu 2\beta$ decay claim. Figure taken from Ref. ⁴⁾.

2.3. Neutrinoless double beta decay versus cosmology plus oscillations

Figure 4 (left) shows the regions allowed at 2σ in normal and inverted hierarchy (slanted bands) by the combination of oscillation results with the first dataset in Table 2 (CMB), in the plane spanned by $(\Sigma, m_{\beta\beta})$. This is the most conservative case, with the weakest limits on Σ , and the largest overlap between the regions separately allowed by oscillation+CMB data and by the $0\nu 2\beta$ claim. The results of a global χ^2 fit are shown as a thick black wedge in the upper right part of the figure. Such global combination would correspond to nearly degenerate masses in the range

$$m_1 \simeq m_2 \simeq m_3 \in [0.15, 0.46] \text{ eV} \quad (2\sigma) .$$

In this case (degenerate spectrum), the preferred range for effective neutrino mass in β decay would also be $m_\beta \in [0.15, 0.46] \text{ eV}$. In the upper half of this range, the KATRIN β^- experiment could make a 5σ discovery, according to the estimated sensitivity. A 3σ evidence could still be found in KATRIN for $m_\beta \sim 0.3 \text{ eV}$. Below this value, the sensitivity would be rapidly degraded, and only upper bounds could be placed for $m_\beta < \sim 0.2 \text{ eV}$.

The right panel in Fig. 3 is analogous to the left one, but refers to the 4th dataset in Table 2 (all cosmo data, including $\text{Ly}\alpha$). In this case, the allowed regions do not overlap and cannot be combined, since the relatively strong cosmological limit $\Sigma < 0.19 \text{ eV}$ implies $m_{\beta\beta} < \sim 0.08 \text{ eV}$, in contradiction with Eq. (4). Solutions to this discrepancy would require that either some data or their interpretation are wrong.

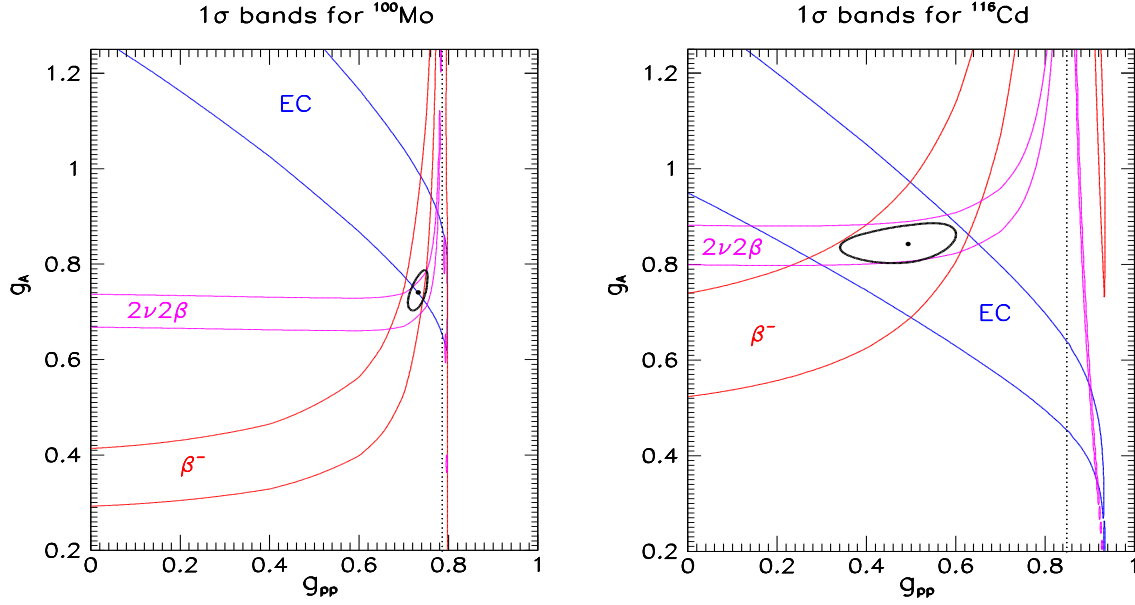


Figure 5: Breakdown of individual constraints in the (g_{pp}, g_A) plane. The slanted bands corresponds to the regions allowed at 1σ level (including experimental and theoretical errors) by β^- , EC, and $2\nu 2\beta$ data. Their combination is shown as a thick ellipse. Left: ^{100}Mo . Right: ^{116}Cd . From Ref. ⁵⁾.

3. NME uncertainties in $0\nu 2\beta$ decay

Constraining NME uncertainties is crucial to compare results from different $0\nu 2\beta$ experiments and to provide well-defined values (or limits) for $m_{\beta\beta}$, as shown in Sec. 2.1. Here we report on an approach to this problem developed in Ref. ⁵⁾ (in collaboration with A. Faessler, V. Rodin, and F. Simkovic) which, although currently limited to two nuclei, appears to be promising.

Estimates of nuclear matrix elements for $0\nu 2\beta$ decay based on the quasiparticle random phase approximations (QRPA) are affected by theoretical uncertainties, which can be substantially reduced by fixing the unknown strength parameter g_{pp} of the residual particle-particle interaction through one experimental constraint — most notably through the two-neutrino double beta decay ($2\nu 2\beta$) lifetime. However, it has been noted that the g_{pp} adjustment via $2\nu 2\beta$ data may bring QRPA models in disagreement with independent data on electron capture (EC) and single beta decay (β^-) lifetimes. Actually, in two nuclei of interest for $0\nu 2\beta$ decay (^{100}Mo and ^{116}Cd), for which all such data are available, we have shown in Ref. ⁵⁾ that the disagreement vanishes, provided that the axial vector coupling g_A is treated as a free parameter, with allowance for $g_A < 1$ (“strong quenching”). Three independent lifetime data ($2\nu 2\beta$, EC, β^-) are then accurately reproduced by means of two free parameters (g_{pp} , g_A), resulting in an overconstrained parameter space.

Overconstraining the (g_{pp}, g_A) parameters is equivalent to state that, in each of the ^{100}Mo and ^{116}Cd reference nuclei, our approach provides one prediction which is experimentally verified. Figure 5 illustrates this statement via the 1σ bands individually allowed by β^- , EC and $2\nu 2\beta$ data for ^{100}Mo and ^{116}Cd . Any two bands can be used to constrain (g_{pp}, g_A) in a closed region (the “prediction”), which is then crossed by the third independent band (the “experimental verification”). As a consequence, the parametric QRPA uncertainties induced by (g_{pp}, g_A) in the $0\nu 2\beta$ decay of these two nuclei are also significantly constrained⁵⁾. We are planning a more systematic study, in order to extend this (or a similar) approach to other nuclei of interest for $0\nu 2\beta$ decay.

4. Conclusions

Since the atmospheric ν oscillation discovery 10 years ago, important pieces of information are being slowly added to the puzzle of absolute ν masses. We have discussed the most recent oscillation and non-oscillation updates in the field, as presented at this NO-VE Workshop—and updated after the recent Neutrino 2008 Conference. Oscillation parameters are robustly constrained, and an intriguing indication for $\theta_{13} > 0$ appears to emerge. Concerning non-oscillation observables, despite some recent experimental and theoretical progress, a coherent picture remains elusive. In particular, the $0\nu 2\beta$ claim is still under independent experimental scrutiny, and it may be compatible or incompatible with the cosmological bounds, depending on data selection (especially $\text{Ly}\alpha$). Reduction of nuclear matrix element uncertainties is also crucial to improve the comparison of different $0\nu 2\beta$ results. A confident assessment of the ν mass scale will require converging evidence from at least two of the three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ within the narrow limits allowed by oscillation data.

5. Acknowledgments

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Note: For the sake of brevity, the following bibliography is essentially limited to some of our recent papers. One can find therein relevant references, as well as credit to previous works, about the vast phenomenology of neutrino masses and mixings.

6. References

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