WHAT HAVE WE LEARNED ABOUT NEUTRINOS?

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ABSTRACT

Solar and atmospheric neutrino data require physics beyond the Standard Model. The simplest global interpretation of the data is in terms of three-neutrino oscillations. I summarize the results of such a global analysis, in particular the bounds on the angle θ_{13} probed in reactor experiments. Even though not implied by the data, bi-maximal neutrino mixing emerges as an attractive possibility either in hierarchical or quasi-degenerate scenarios of neutrino mass. However, present solar neutrino data by no means imply neutrino oscillations since there are equally good alternative explanations such as resonant spin flavor precession.

1. Introduction

Undoubtedly the solar [1)] and atmospheric [2,3)] neutrino problems provide the two milestones indicating physics beyond the Standard Model (SM). Of particular importance has been the confirmation in 1998 by the Super-Kamiokande (SK, for short) collaboration of the zenith-angle-dependent deficit of atmospheric neutrinos. Altogether the data provide a strong evidence for ν_e and ν_μ conversions, respectively. Neutrino conversions are a natural consequence of theories beyond the Standard Model [4)]. The first example is oscillations of low-mass neutrinos. While the theoretical understanding of the origin of neutrino masses is still lacking, there is a variety of attractive options available. Most likely, the exceptional nature of neutrinos as the only electrically neutral fermions in the SM underlies the smallness of their mass, as it would be associated with the violation of lepton number. Indeed in gauge theories one expects, on fundamental grounds, neutrinos to be Majorana fermions [5)]. This is the generic situation in actual models. It will be surprising indeed if massive neutrinos turn out to be Dirac particles, like the quarks. Lepton number violation would imply processes such as neutrinoless double beta decay [6)], novel CP violation effects [5,7)], and/or neutrino electromagnetic properties [8)], so far unobserved. Present data are compatible with either hierarchical or quasi-degenerate neutrino masses. While solar neutrino rates favour the small mixing angle MSW oscillations [9,10)], present data on the recoil-electron spectrum prefer the large mixing solutions. When interpreted in terms of neutrino oscillations, the observed atmospheric neutrino zenith-angle-dependent deficit strongly suggests the existence of ν_μ to ν_τ oscillations with maximal mixing [11)]. Adding information from reactor experiments one concludes that the third angle amongst the three neutrinos is small [12)]. Thus, altogether, we have the intriguing

possibility that, unlike the case of quarks, neutrino mixing is bi-maximal [13,14,15,16,17] which could be tested at the upcoming long-baseline experiments or at a neutrino factory experiment [18] or at the proposed KamLAND experiment [19].

In addition to the above, there is also a long history of searches for neutrino oscillations at accelerators. Except for the unconfirmed hint provided by the LSND experiment [20,21], these have so–far been negative. The resulting limits, however, are not very restrictive on the scale of the indications from underground experiments and we will not discuss any further. Barring exotic neutrino conversion mechanisms the hint of the LSND experiment together with the solar and atmospheric data require *three mass scales*, hence the need for a fourth light neutrino, which must be sterile [22,23,24,25,26]. The most attractive possibility is to have, out of the four neutrinos, two of them lie at the solar neutrino scale, with the other two maximally-mixed neutrinos at the LSND scale [22,23,25]. These schemes have distinct implications at future solar & atmospheric neutrino experiments with sensitivity to neutral current neutrino interactions such as SNO. Cosmology can also place restrictions on these four-neutrino schemes [27].

2. Indications for New Physics

The most solid hints in favour of new physics in the neutrino sector come from underground experiments on solar [1] and atmospheric [2,3] neutrinos. Here I consider data corresponding to 1117–day solar and 1144–day (71 kton-yr) atmospheric SK samples, respectively. There are also new data from Soudan-2 (5.1 kton-yr) and MACRO.

2.1. Solar Neutrinos

Our sun produces ν_e's through various nuclear reactions which take place in its interior. The predicted spectrum of solar neutrinos is illustrated in Fig. (1), taken from [28]. I will refer to this model as "the" Standard Solar Model (SSM). Solar neutrinos are detected either with geochemical methods (the $\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^-$ reaction at the Homestake experiment and the $\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$ reaction at the Gallex, Sage and GNO experiments) or through $\nu_e e^-$ scattering on water, using Cerenkov techniques at Kamiokande and Super-Kamiokande. As summarized in Fig. (2) all experiments observe a deficit of 30 to 60 % whose energy dependence follows mainly from the lower Chlorine rate. Note that Fig. (2) includes the results from SK, SAGE & GNO presented at ν2000, but not the first results from SNO. It is convenient to present the predictions of various standard solar models in terms of the ^{7}Be and ^{8}B neutrino fluxes, normalized to the SSM predictions [28], as seen in Fig. (3), which includes most of the existing solar models.

On the other hand the values of the fluxes indicated by measured neutrino event rates are shown by the contours in the lower-left part of the figure, with a nega-

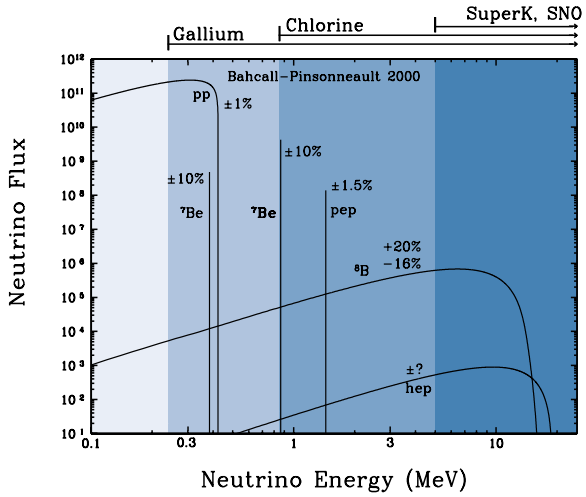

Figure 1: Bahcall–Pinsonneault solar neutrino fluxes

tive best-fit ^{7}Be neutrino flux! This discrepancy strongly suggests the need for new particle physics [29]. Since possible non-standard astrophysical solutions are rather constrained by helioseismology studies [28] one is led to assume the existence of neutrino conversions, such as those induced by very small neutrino masses.

The high statistics of SK after 1117 days of data–taking also provides very useful information on the recoil electron energy spectrum with event rates given for 18 bins starting at 5.5 MeV The spectrum in Fig. (4) is well described by the flat hypothesis $\chi^2_{flat} = 13/(17\text{dof})$, in contrast with hints from previous 825–day sample. Moreover, SK measures the zenith angle distribution (day/night effect) which is sensitive to the effect of the Earth matter in the neutrino propagation. One sees a slight excess of events at night, but the corresponding day versus night asymmetry $A_{D/N} = \frac{D-N}{\frac{D+N}{2}} = -0.034 \pm 0.022 \pm 0.013$ is only 1.3σ away from zero. In order to combine this day–night information with the spectral data, SK has also presented separately the measured recoil energy spectrum during the day and during the night. This will be referred in the following as the day–night spectra data and contains 2×18 data bins.

Note that the absence of clear hints of spectral distortion, day-night or seasonal variation implies that, *per se*, they do not give any clear indication for physics beyond the standard model. From this point of view, despite the increasing weight of such rate-independent observables, the solar neutrino problem rests heavily on the rate discrepancy. Nevertheless, as we will see, rate-independent observables are playing an important rôle in selecting amongst different solutions of the solar neutrino problem.

2.2. Atmospheric Neutrinos

Neutrinos produced as decay products in hadronic showers from cosmic ray col-

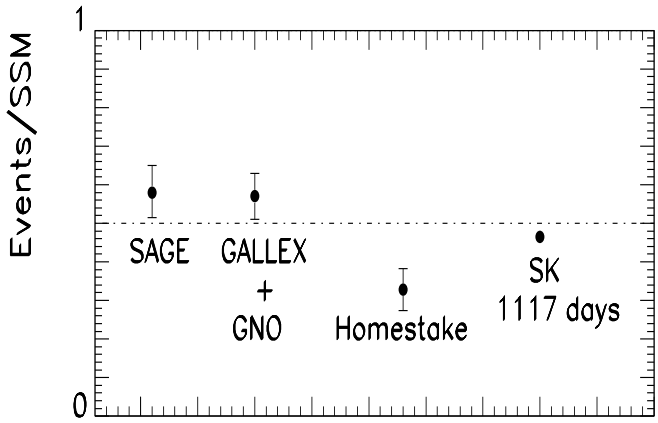

Figure 2: Solar neutrino event rates normalized to SSM prediction.

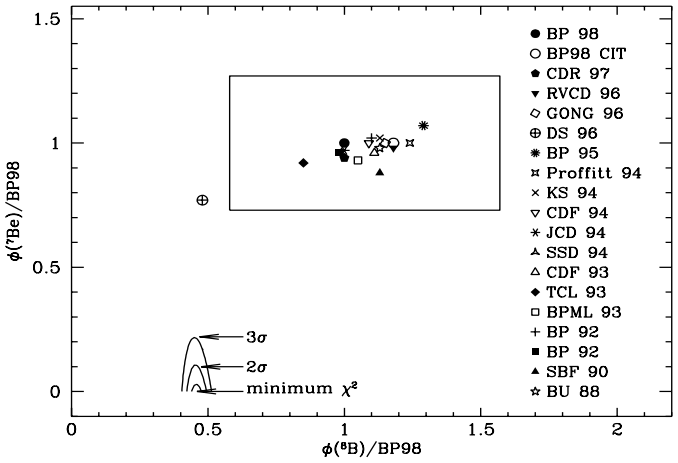

Figure 3: ^{7}Be and ^{8}B neutrino fluxes: theory versus data

lisions with nuclei in the upper atmosphere have been observed in several experiments [2,3]. Although individual ν_μ or ν_e fluxes are only known to within 30% accuracy, their ratio is predicted to 5% over energies that vary over three orders of magnitude, from 0.1 GeV to 100 GeV [30]. The long-standing discrepancy between the predicted and measured μ/e ratio of the muon $(\nu_\mu + \bar{\nu}_\mu)$ over the electron atmospheric neutrino flux $(\nu_e + \bar{\nu}_e)$ [31] found both in water Cerenkov experiments (Kamiokande, SK and IMB) as well as in the iron calorimeter Soudan2 experiment is illustrated in Fig. (6). This evidence has now been substantially strengthened by the fact that it exhibits a strong *zenith-angle dependence* [2] as can be seen from Fig. (7). The zenith-angle distributions for the Super-Kamiokande e–like are shown in the left panels, both in the sub-GeV (upper panels) and multi-GeV (lower panels) energy range. The thick solid line is the expected distribution in the SM. It is consistent with the SM expectations. In contrast μ–like events displayed in the right-panels show a clear deficit of neutrinos

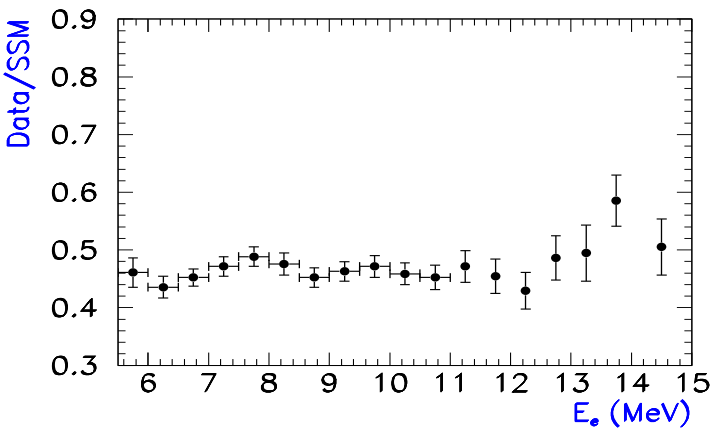

Figure 4: Measured solar recoil electron energy spectra [1)]

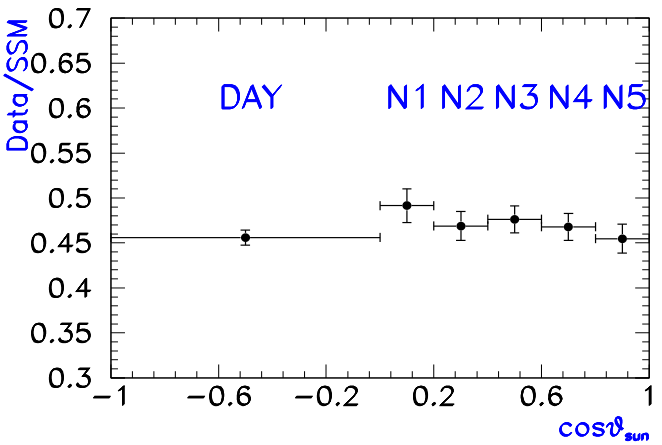

Figure 5: Zenith angle distribution normalized to the SSM prediction.

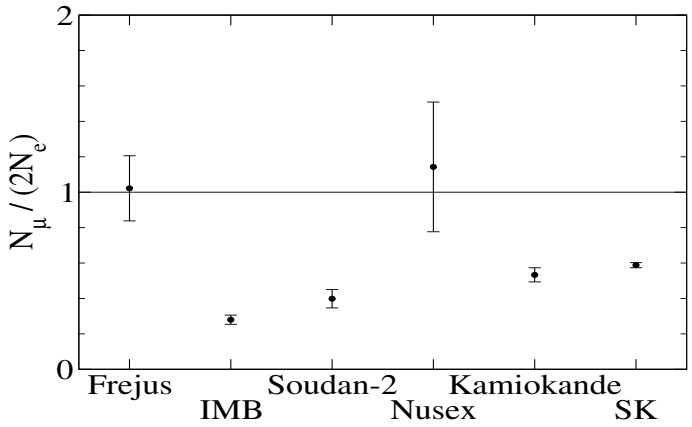

Figure 6: Atmospheric neutrino event rates normalized to theory

coming from below, which is very suggestive indeed of ν_μ oscillations. In Fig. (7) we also give the predicted best-fit distributions obtained in a global 3-neutrino oscillation description of the data [11]. The thin full line is the prediction for the overall best-fit point of the contained plus up-going atmospheric data sample, with $\tan^2\theta_{13} = 0.025$, $\Delta m^2_{32} = 3.3 \times 10^{-3}$ eV^2 and $\tan^2\theta_{23} = 1.6$.

Zenith-angle distributions have also been recorded for upward-going muon events in Super-Kamiokande and MACRO, as illustrated in Fig. (8). The thick solid line is the expected distribution in the SM, while the thin full line corresponds, as in Fig. (7), to the prediction for the overall global best-fit point.

3. Three–neutrino fits

The most economical joint description of solar and atmospheric anomalies involves oscillations amongst all three known types of neutrinos. Here I summarize the results of the recent global analysis [11] of the solar [1], atmospheric [2,3] and reactor [12] neutrino data in terms of three–neutrino oscillations. The present discussion goes beyond previous three–neutrino oscillation analyses including only solar [32] or only atmospheric neutrino data [33]. It also updates earlier joint studies [34]. As we saw the solar neutrino data includes the recoil electron energy spectra for day and night periods. On the other hand the atmospheric data sample includes not only contained events but also the upward-going ν-induced muon fluxes. In addition to previous Frejus, IMB, Nusex, and Kamioka data we use the most recent 71 kton-yr (1144 days) SK data set, the 5.1 kton-yr contained events of Soudan2, and the results on up–going muons from the MACRO detector.

The pattern of neutrino oscillations expected in any fundamental (gauge) theory of neutrino mass is determined by the structure of the lepton mixing matrix [4,35]. For the simplest three–neutrino theories this is in general characterized by three mixing angles and three CP violating phases [5]. The latter include, in addition to the

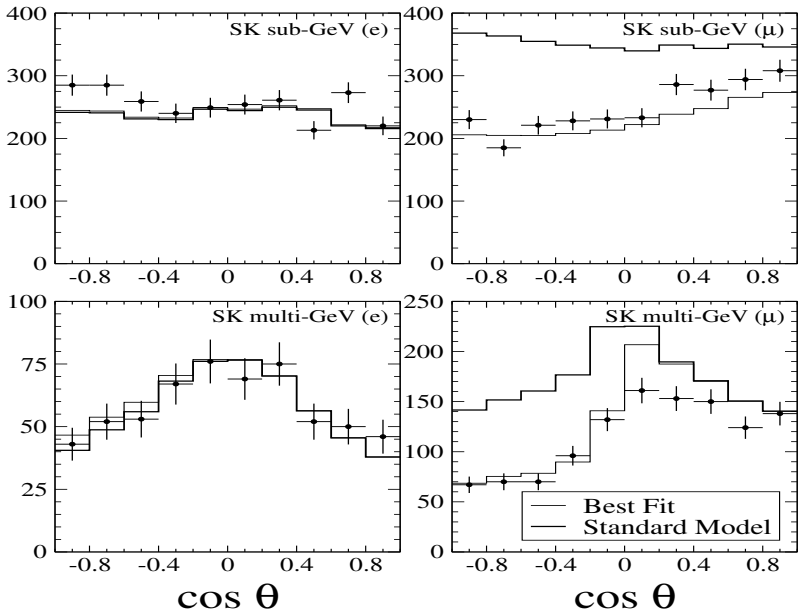

Figure 7: SK zenith-angle distributions for contained events compared with theoretical expectations within and without the oscillation hypothesis

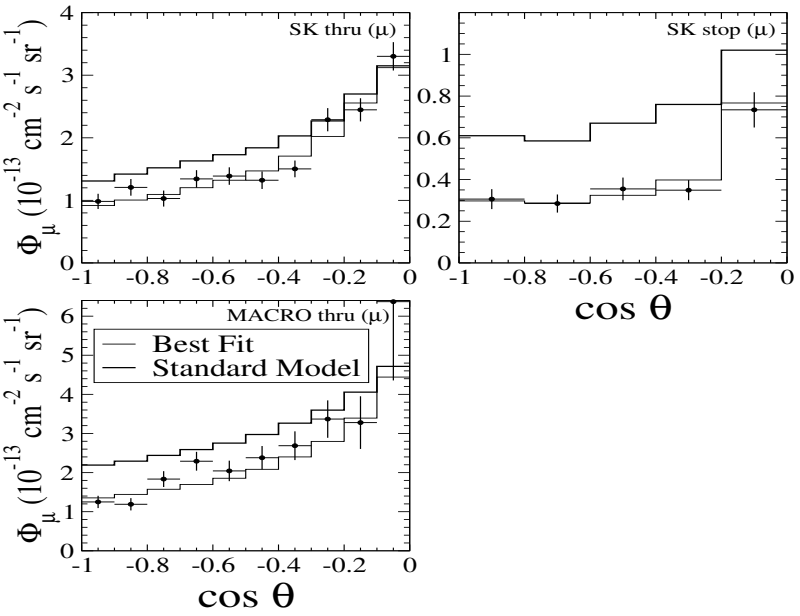

Figure 8: Zenith-angle distributions for upward-going muons in Super-Kamiokande and MACRO.

Dirac-type phase analogous to that of the quark sector, two extra physical [7] phases associated to the Majorana character of neutrinos. Conservation of CP implies that Dirac phases are zero modulo π, while Majorana phases are zero modulo$\pi/2$ [36,8]. For our following discussion all three phases are set to zero. In this case the mixing matrix can be conveniently chosen in the form [5]

$$\begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix} \tag{1}$$

This way the joint study of solar and atmospheric neutrino oscillations will be characterized by a five-dimensional parameter space

$$\begin{array}{ll} \Delta m^2_{\odot} & \equiv \Delta m^2_{21} = m^2_2 - m^2_1 \\ \Delta m^2_{atm} & \equiv \Delta m^2_{32} = m^2_3 - m^2_2 \\ \theta_{\odot} & \equiv \theta_{12} \\ \theta_{atm} & \equiv \theta_{23} \\ \theta_{reactor} & \equiv \theta_{13} \end{array} \tag{2}$$

where all mixing angles are assumed to lie in the full range from $[0, \pi/2]$.

From the required hierarchy in the splittings $\Delta m^2_{atm} \gg \Delta m^2_{\odot}$ indicated by the solutions to the solar and atmospheric neutrino anomalies (see below) it follows that the analyses of solar data constrain three of the five independent oscillation parameters, namely, $\Delta m^2_{21}, \theta_{12}$ and θ_{13} since for most cases oscillations over the atmospheric scale average out. Conversely, from the point of view of the atmospheric data analysis one can effectively assume that the lighter neutrinos become degenerate so that one can rotate away the corresponding angle θ_{12} leading to the simplified form [37]

$$\mathbf{R} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -s_{13}c_{23} & -s_{23} & c_{23}c_{13} \end{pmatrix}; \tag{3}$$

for the leptonic mixing matrix. As a result only three oscillation parameters: Δm^2_{32}, θ_{23} and θ_{13} are necessary to describe the 3-neutrino propagation of atmospheric neutrinos.

It follows from the above discussion that θ_{13} is the only parameter common to both analyses and may potentially allow for some "cross-talk" between the two sectors. It is known that for $\Delta m^2_{32} \gg \Delta m^2_{12}$ and $\theta_{13} = 0$ the atmospheric and solar neutrino oscillations decouple in two 2–ν oscillation scenarios. In this respect our results also contain as limiting cases the pure two–neutrino oscillation scenarios and update previous analyses on atmospheric neutrinos [38,39] and solar neutrinos [40,28].

In order to compute the solar neutrinos survival probabilities for any value of the neutrino mass and mixing the full expression for the survival probability has been used, without appealing to the usual approximations whose validity defines the

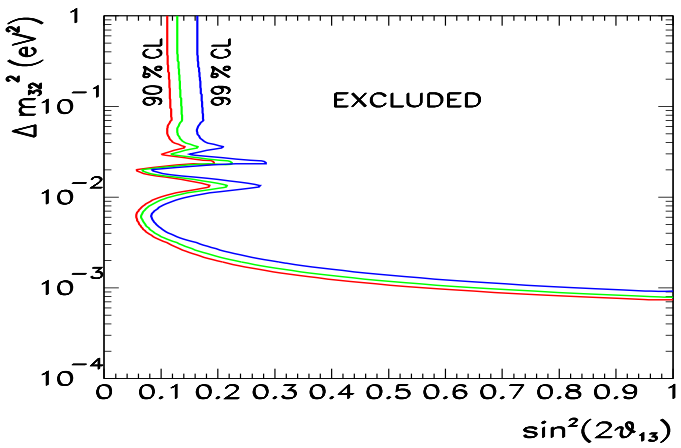

Figure 9: Region in Δm^2_{32} and $\sin^2(2\theta_{13})$ excluded by the Chooz reactor.

MSW [10] or the " just-so" [41] regime. This treatment of neutrino oscillations is therefore unified, with MSW and vacuum oscillations considered on the same footing. Likewise, it includes conversions in the "dark-side", i. e. with $\theta_{12} > \pi/4$ [42]. Results are found by numerically solving the Schrodinger neutrino evolution equation in the Sun and the Earth matter, using the electron number density of BP2000 model [43] and the Earth density profile given in the Preliminary Reference Earth Model (PREM) [44].

Reactor limits

To start the summary of the global 3-neutrino fits we first note that, of all laboratory searches for neutrino oscillation, reactors provide the most sensitive one when it comes to comparing with the data from underground experiments. Thus we will first consider the region of oscillation parameters which can be excluded from reactor experiments. The restrictions on Δm^2_{32} and $\sin^2(2\theta_{13})$ that follow from the non observation of oscillations at the Chooz reactor experiment are shown in Fig. (9), taken from [11]. The curves represent the 90, 95 and 99% CL excluded region defined with 2 d. o. f. for comparison with the Chooz published results. In what follows we will compare this direct bound with those obtained from a global analysis of solar and atmospheric data, as well as consider its effect in combination with the latter.

Solar data fit

We first present the allowed regions of solar oscillation parameters θ_{12}, Δm^2_{21} as a function of θ_{13}. All plots are taken from [11] where details of the analysis can be found. In Fig. (10) we give the allowed three–neutrino oscillation regions in Δm^2_{21} and $\tan^2\theta_{12}$ from the measurements of the total event rates at the Chlorine, Gallium, Kamiokande and Super-Kamiokande experiments. The different panels repre-

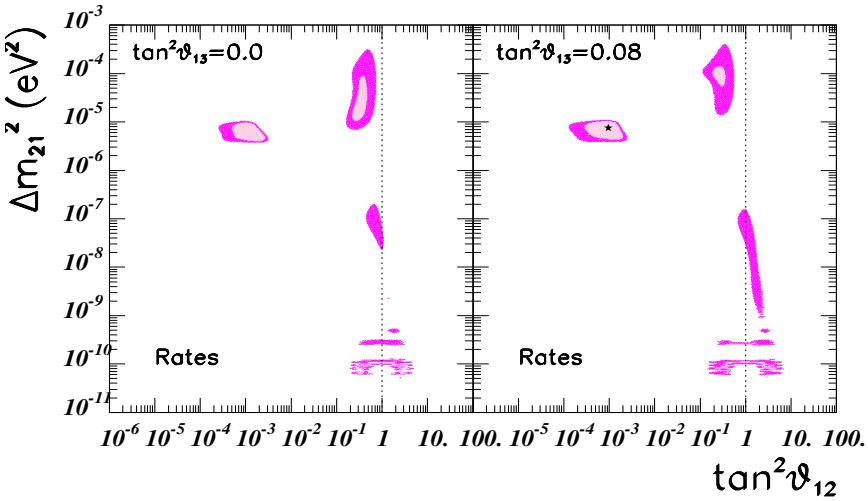

Figure 10: 3-ν oscillation regions `allowed` at 99% (darker) and 90% CL (lighter) by measurements of the total solar neutrino event rates. The best–fit is for SMA.

sent the `allowed` regions at 99% (darker) and 90% CL (lighter) obtained as sections for fixed values of the mixing angle $\tan^2\theta_{13}$ of the three–dimensional volume defined by $\chi^2 - \chi^2_{min}$=6.25 (90%), 11.36 (99%). The best–fit point is denoted as a star. It occurs, as expected, for the small mixing MSW solution (SMA) simply because this is the situation which most strongly suppresses the unwanted ^{7}Be neutrino flux. It is characterized by a non-zero θ_{13} value. For higher θ_{13}, the description worsens. Although relatively weak, the limit on θ_{13} from solar data is totally independent on the allowed range of the atmospheric mass difference Δm^2_{32}.

The three–neutrino solar oscillation regions `excluded` by the measurement of the day–night spectra data in the Super-Kamiokande 1117-day data sample is illustrated in Fig. (11).

Finally, the `allowed` three–neutrino solar oscillation regions in Δm^2_{21} and $\tan^2\theta_{12}$ which follows from the global analysis of all solar neutrino data is presented in Fig. (12). The best–fit point now shifts to LMA, as indicated.

The relative quality of the various oscillation solutions of the solar neutrino problem is illustrated in Fig. (13). This figure gives $\Delta\chi^2$ as a function of $\tan^2\theta_{13}$ from the 3–neutrino analysis of the solar data. The dotted horizontal lines correspond to the 90%, 99% CL limits. The left panel corresponds the analysis of total rates only, while the right panel corresponds to the global analysis. The dotted horizontal lines correspond to the 90%, 99% CL limits. Although all the various SMA, LMA, LOW and vacuum solutions provide acceptable global descriptions of the solar data, they are not equally good. From the right panel in Fig. (13) we conclude that, for small enough $\tan^2\theta_{13}$ values (so that we gets effectively a two-neutrino scheme) the LMA solution is the best, while SMA is the worst. One notices also that the electron recoil energy day-night spectra, are playing an increasing role in discriminating between

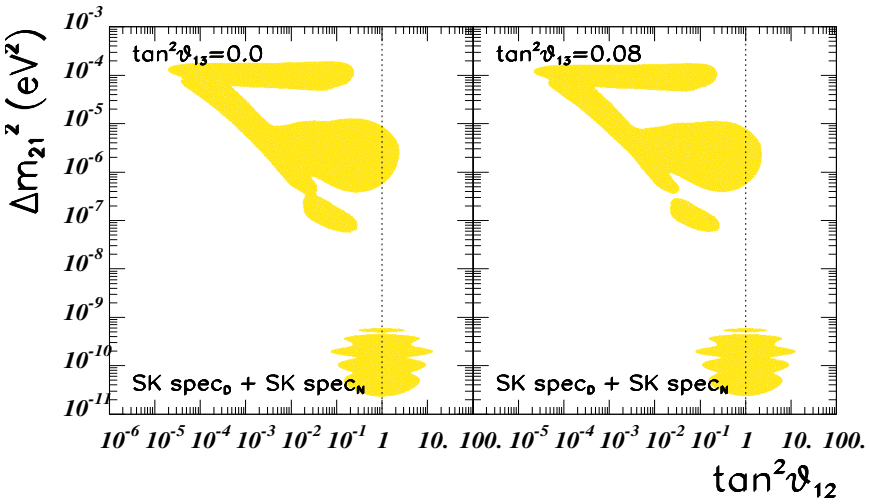

Figure 11: 3-ν oscillation solar oscillation regions `excluded` at 99% CL by the day–night spectra.

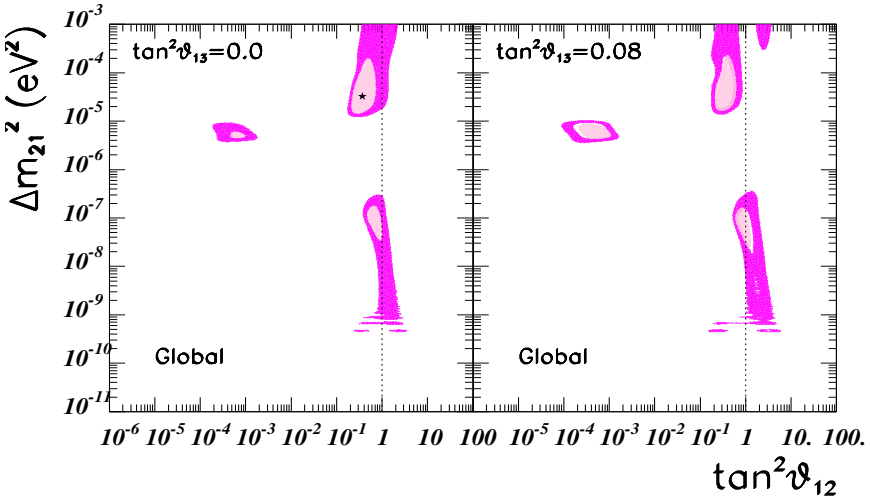

Figure 12: 3-ν oscillation regions `allowed` by all of the solar neutrino data. The best–fit is for LMA.

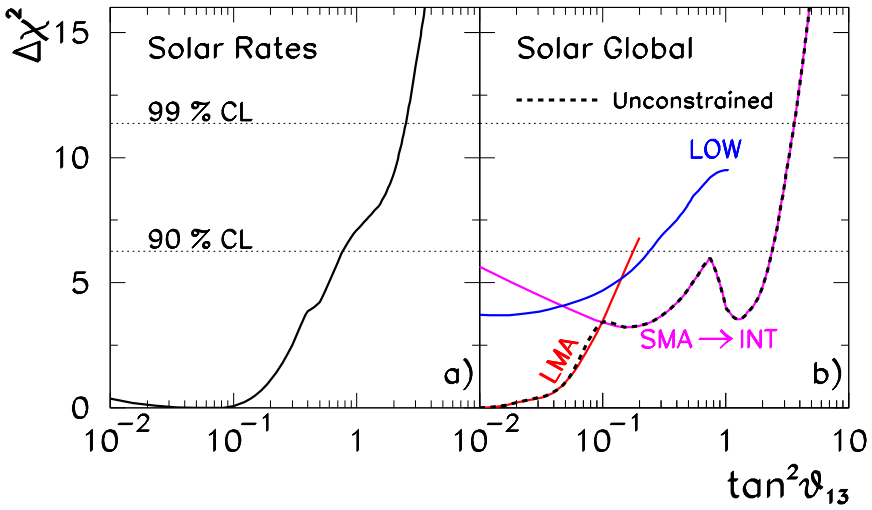

Figure 13: Relative quality of three–neutrino solutions to the solar neutrino problem.

different solutions to the solar neutrino problem, pushing the best–fit point towards the LMA solution [11], a trend already noted in earlier 2-neutrino analyses due to the same reason [40].

Since the characteristic average energies of different neutrino flavours is different in a supernova, one expects that neutrino oscillations have a potentially important impact on the observed $\bar{\nu}_e$ signal of supernova SN 1987A [45]. This issue has been recently re-analysed in ref. [46]. Performing a maximum-likelihood analysis using as fit parameters the released binding energy $E_{\rm b}$ and the average neutrino energy $\langle E_{\bar{\nu}_e} \rangle$, it has been found that $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ oscillations with large mixing angles have lower best-fit values for $\langle E_{\bar{\nu}_e} \rangle$ than small-mixing angle (SMA) oscillations. Moreover, the inferred value of $\langle E_{\bar{\nu}_e} \rangle$ is already in the SMA case lower than those found in simulations. This conflict had been previously interpreted [45] as evidence against the large mixing oscillation solutions to the solar neutrino problem. The more detailed analysis given in ref. [46] has found, however, that the LMA-MSW solution is not really in any serious conflict with the current understanding of SN physics. In contrast, the vacuum oscillation and the LOW solutions to the solar neutrino problem can be excluded at the 4σ level for most of the SN parameter ranges found in simulations. Only a marginal region with low values of $\langle E_{\bar{\nu}_e} \rangle$, $< E_{\bar{\nu}_{\mu,\tau}} >$ and $E_{\rm b}$ is possible, in which these oscillation solutions can be reconciled with the neutrino signal of SN 1987A.

Another issue which could play a more significant role in future investigations is that of seasonal variations, expected in the just-so regime and, more subtly, also in the MSW large mixing solutions, LMA and LOW. The first would result from the eccentricity of the Earth's orbit around the Sun and could be tested by searching for seasonal variations in the ^{7}Be neutrino flux at the Borexino experiment, and possibly at KamLAND [47]. The latter would result from the regeneration effect at the Earth (day-night effect) and might be tested through time variations of event rates at GNO

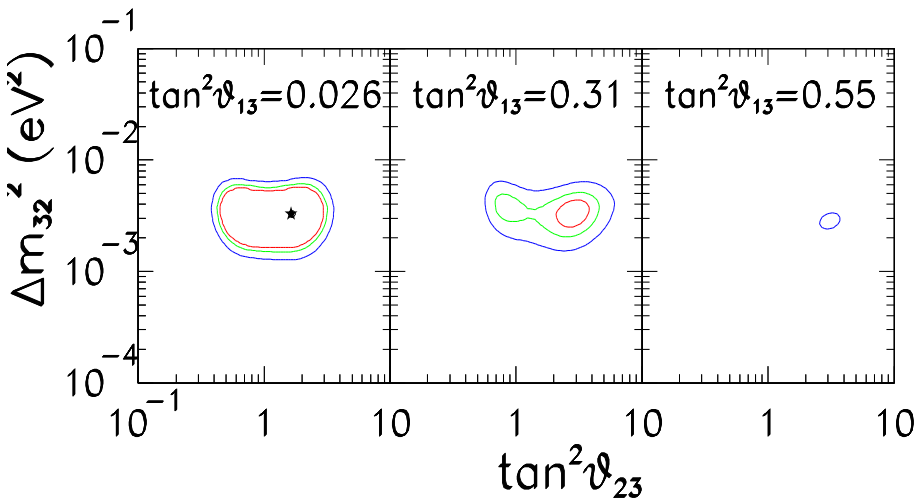

Figure 14: 90, 95 and 99% CL $(\tan^2\theta_{23}, \Delta m^2_{32})$ regions `allowed` by combining all atmospheric data.

and Borexino [48].

An interesting theoretical issue is the possible effect that random fluctuations in the solar matter density [49,50,51] may have on the solar neutrino event rates. The existence of such noise fluctuations at a few percent level is not excluded by present helioseismology studies. The correlation length L_0 associated with the scale of the fluctuation can be assumed to lie between the mean free path of the electrons in the solar medium, $l_{free} \sim 10$ cm, and the neutrino oscillation length in matter, λ_m, e. g. $l_{free} \ll L_0 \ll \lambda_m$. Even small fluctuations can have an important effect on averaged solar neutrino survival probabilities, especially for small solar mixing angles [49,50]. The fluctuations can affect the ^{7}Be neutrino component of the solar neutrino spectrum, implying that Borexino can probe, at some level of precision, the magnitude of solar matter density fluctuations [52].

Atmospheric and reactor data fit

Here I present the allowed regions of atmospheric oscillation parameters θ_{23}, Δm^2_{32} for different values of the parameter θ_{13}, common to solar and atmospheric analyses. All plots are taken from [11] where details can be found. In Fig. (14) we display the `allowed` $(\tan^2\theta_{23}, \Delta m^2_{32})$ regions for different $\tan^2\theta_{13}$ values, that follow from the combination of Super-Kamiokande atmospheric neutrino events. The regions refer to 90, 95 and 99% CL. The best–fit point is denoted as a star and corresponds to $\tan^2\theta_{13} = 0.026$. In Fig. (15) we present the three–neutrino regions in $(\tan^2\theta_{23},\ \Delta m^2_{32})$ `allowed` by the combination of all atmospheric neutrino data plus Chooz. The best–fit point is denoted as a star. Comparing Fig. (14) and Fig. (15) one can see the weight of the reactor neutrino bound on the global analysis. The best global fit has $\tan^2\theta_{13} = 0.005$ and for $\tan^2\theta_{13} = 0.075$ even the 99% CL allowed

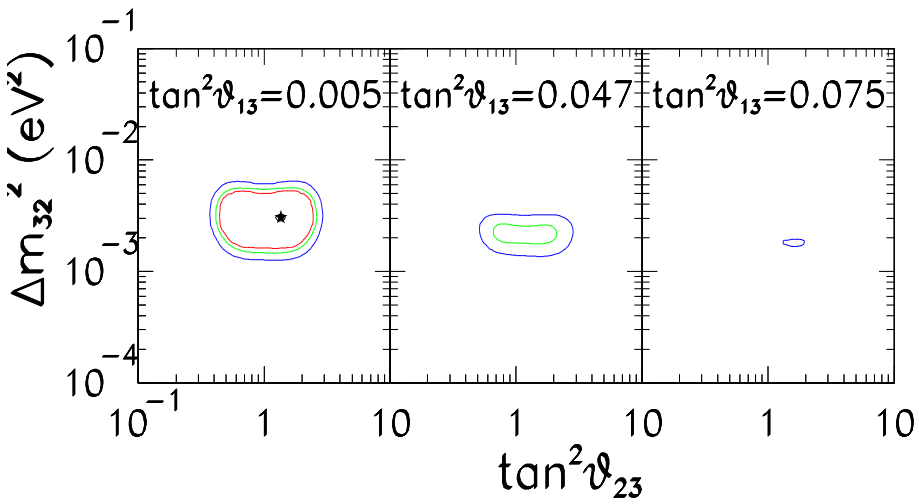

Figure 15: 90, 95 and 99% CL 3–ν ($\tan^2\theta_{23}$, Δm^2_{32}) regions `allowed` by combining all neutrino data.

region disappears. Notice the important complementarity between atmospheric data and the strong reactor limits on θ_{13} since the latter apply only for $\Delta m^2_{32} \gtrsim 10^{-3}$ eV^2.

Combining solar, atmospheric and reactor data

We also obtain the allowed ranges of parameters from the full five–dimensional combined analysis of all of the above neutrino data. In Fig. (16) we give the regions in Δm^2_{21} and $\tan^2\theta_{12}$ `allowed` by the global analysis of solar, atmospheric and reactor neutrino data. The left panel gives the regions for the unconstrained analysis defined in terms of the increases of $\Delta\chi^2$ for 5 d.o.f. from the global best fit point denoted as a star. The right panel shows the values of $\tan^2\theta_{13}$ beyond which the 99% CL region starts to disappear.

4. Putting all pieces together

Altogether these data give a strong evidence for physics beyond the Standard Model. Small neutrino masses provide the simplest and most generic explanation for both. Theoretical neutrino mass models can lead to either hierarchical [15,53,17] or quasi-degenerate [16,54] neutrinos. Top-bottom approaches inspired by the idea of Unification typically employ either a see-saw mechanism, or high dimension operators. As examples of such models I mention two we have recently investigated. The first is a minimalistic model which leads to vacuum solution to the solar neutrino problem [15]. The second is a model based on the idea that, like the gauge couplings characterizing the electro-weak and strong interactions unify at high energies (in the presence of supersymmetry), so do the neutrino masses. Indeed, present neutrino

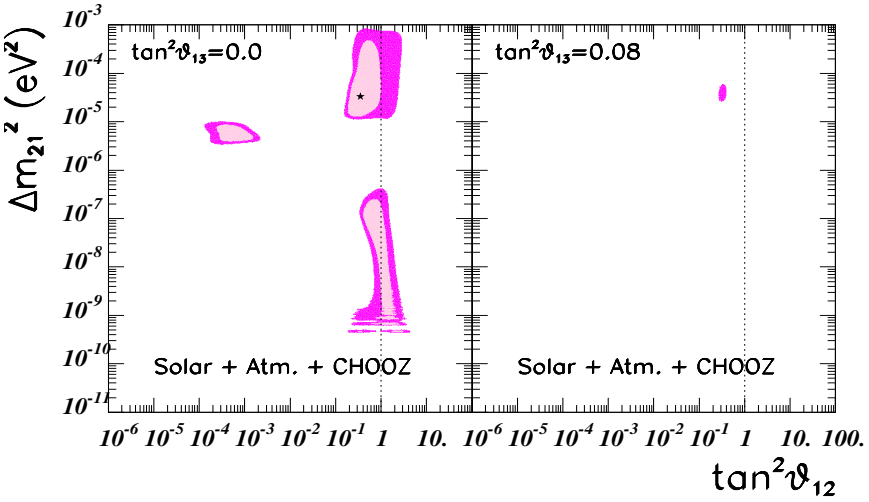

Figure 16: $(\Delta m^2_{21}, \tan^2\theta_{12})$ regions allowed by the `global` neutrino data analysis.

data are consistent with neutrino masses arising from a common seed at some "neutrino unification" scale M_X [16]. Such a simple theoretical ansatz is very predictive and rules out the SMA solution, leading naturally to quasi-degenerate neutrinos that could lie in the electron-volt range. Neutrino mass splittings are induced by renormalization effects associated with supersymmetric thresholds. In contrast to other models, degeneracy obtained in this way avoids problems of naturalness [55] since the two leading mass-eigenstate neutrinos present in ν_e form a pseudo-Dirac neutrino, suppressing neutrinoless double beta decay.

Supersymmetry with bilinear breaking of R–parity provides a simple bottom-up-type model which allows for the possibility of probing the neutrino mixing also the context of high–energy collider experiments such as the LHC [53]. The effective bilinear nature of the breaking of R parity may arise from its spontaneous origin [56] or else be required in models with extra symmetries, such as an anomalous $U(1)_H$ horizontal symmetry [17]. The latter can also justify the required relatively small strength of R–parity violation. For additional models and for models involving specific Yukawa textures see [14,57,58].

Last, but not least, I mention that it is impossible to reconcile solar, atmospheric and reactor data with the LSND hint in terms of neutrino oscillations without a light sterile neutrino [22,23]. The small LSND scale may arise due to its radiative nature [22,23] or from volume suppression in extra dimension models where the sterile neutrino is put "in the bulk" [60]. In contrast the splittings among the neutrinos may arise either from loop suppression [22,23] or from the violation of R parity [25]. Additional references may be found in [24] and for a more complete discussion of limits on 4-neutrino models see [26]. If light sterile neutrinos exist they should be probed at

neutral-current-sensitive solar and atmospheric neutrino experiments such as SNO [59].

5. Conclusion

The solar neutrino data gives a strong evidence for ν_e *conversion*, but by no means imply neutrino oscillations since there are equally good alternative explanations. In contrast the angle-dependent atmospheric neutrino deficit provides a stronger case in favour of genuine ν_μ *to* ν_τ *oscillations*. Within the oscillation framework the combined data suggest the intriguing possibility of bi-maximal neutrino mixing. This would dramatically illustrate the sharp contrast between the lepton and quark sectors of the theory. Future long-baseline oscillation searches should give an independent check of the atmospheric neutrino anomaly, while the prospects for detecting leptonic CP violation at a neutrino factory [18] crucially hinge upon the magnitude of the parameter $\tan^2\theta_{13}$ constrained by the global analysis of reactor, atmospheric and solar neutrino data as discussed above. Upcoming solar neutrino experiments such as SNO and KamLAND [19] should contribute substantially to select amongst various oscillation solutions to the solar neutrino problem through the search for neutral current and/or seasonal effects.

High–energy collider experiments [61] may provide an independent test the neutrino mixing angles involved in the explanation of the neutrino anomalies. An amusing example illustrating such a synergy between accelerator and underground experiments is provided by the idea that low energy supersymmetry with the simplest form of R parity breaking provides the origin for neutrino mass and mixing [53].

On the other hand if the LSND result stands the test of time, this would provide a strong indication for the existence of a light sterile neutrino, again pointing towards a radical departure between leptons and quarks.

However, as already mentioned, the neutrino oscillation interpretation of solar neutrino anomalies is still far from unique. A very good alternative is provided by neutrino resonant [62] spin flavor precession [8] in the magnetic field of the convective zone of the Sun. Such effect would result from neutrinos having non-zero Majorana transition magnetic moments [8]. A recent dedicated analysis of all solar neutrino data using this mechanism can be found in the first paper of ref. [63]. The study reveals an excellent global fit of the data, even better than that provided by the LMA solution. In contrast to the oscillation solutions, neutrino mixing is not required in this case. From this point of view, it is still too early to infer precise neutrino mass and mixing parameters based only on an oscillation analysis of solar neutrino data.

Last, but not least, let me mention that in fifty years of weak interaction physics an answer to the most fundamental question about the nature - Dirac versus Majorana - of neutrinos has so far defied all experimental attempts.

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