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The solar neutrino puzzle: present situation and future scenarios

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Abstract

We present a short review of the existing evidence in favor of neutrino mass and neutrino oscillations which come from different kinds of experiments. We focus our attention in particular on solar neutrinos, presenting a global updated phenomenological analysis of all the available data and we comment on different possible future scenarios.

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1 Introduction

Seventy years after Pauli's ¹⁾ proposal of its existence and almost half a century after its discovery ²⁾, the neutrino still plays a central role in elementary particle physics. The main problem of determining whether it is a massive or massless particle seems to have been solved after the last evidences, coming mainly from the solar and atmospheric neutrino experiments, but we still have to answer important questions. We don't know, for instance, whether it is a Majorana or Dirac particle, nor have we a unique natural explanation of its lightness ³⁾.

The problem of searching for neutrino mass and studying the oscillation phenomenon has been faced in the past through many different experimental techniques. The first studies, based on the so called Fermi-Perrin method of the observation of the β spectrum near the end point, gave ⁴⁾ the limit $m_\nu \leq 500$ MeV. This limit was obviously lowered many times in the following years, up to the present results ⁵⁻⁷⁾.

Since the experiment of Goldhaber et al. ('58) ⁸⁾, we know that neutrinos produced in β decays are left-handed particles. This fact at the beginning appeared as a confirmation of the hypothesis that the neutrino is a massless particle.

Another milestone in the development of our knowledge of neutrino physics was the idea suggested by Pontecorvo ⁹⁾ that neutrino can "oscillate", in the sense that the flavor states are superposition of different mass states. This was a revolutionary hypothesis, because only the electronic neutrino was known in those days, but nowadays we have strong experimental hints that would confirm the validity of Pontecorvo's idea.

Coming to our days, in the usual version of the Standard Model that describes the electroweak interactions, the neutrino is a left handed Dirac particle; hence, in such a theory it is impossible to build a renormalizable mass term for this particle. On the other hand, as we are going to see in detail, there is experimental evidence that it is a massive and oscillating particle. Therefore we are forced by the data to enlarge this "minimal version" of the Standard Model and possibly to build a more general theory in which a neutrino mass can be fitted naturally.

Neutrino physics can be considered an ideal playground to test different theories beyond the Standard Model, like, for instance, supersymmetry and grand unification theories ¹⁰⁾ or the theories based on the existence of large extradimensions ¹¹⁾. The determination of the value of neutrino mass also has important implications on cosmological models. In particular neutrino is a candidate for dark matter and this fact determined a revival of astrophysical studies of neutrino properties in the last decade ¹²⁾.

2 Evidences of neutrino mass and oscillations

All the experiments aiming to measure the neutrino mass and to test the existence of oscillations can be classified in some main categories.

First of all there are the direct kinematical searches like the ones of (5–7) and the searches for the neutrinoless double β decays (13, 14). The present limits on the values of ν_τ and ν_μ masses are (5, 6):

$$\begin{aligned} m(\nu_\tau) &< 18.2 \text{ MeV} \\ m(\nu_\mu) &< 190 \text{ keV} . \end{aligned} \tag{1}$$

The best limits for the mass of the electron neutrino, instead, have been obtained from the Mainz and the Troitsk (15, 16) experiments which have found $m(\nu_e) < 2.2 \text{ eV}$. In future many experiments will try to lower this limit. In particular there is a great expectation for KATRIN (the Karlsruhe Tritium Neutrino experiment) (17), that should start data taking in 2007 and improve the sensitivity down to 0.35 eV .

The search for neutrinoless double β decays is important because the observation of these decays would be a clear indication in favor of a Majorana nature of the neutrino, if we assume CPT invariance (19). The most stringent limit on this process available at the moment comes from the Heidelberg-Moskow collaboration (13) $\langle m_\nu \rangle < 0.35 \text{ eV}$ and from IGEX (International Germanium Experiment) (14) $\langle m_\nu \rangle < 0.33 - 1.35 \text{ eV}$. In the last year there has been a claim (18) from some members of the Heidelberg-Moskow collaboration of discovery of a 2.2σ effect that would be a signal of neutrinoless double β decay, but this result has been strongly contested and the discussion on its validity is still an open question.

A second group of experiments uses neutrino fluxes produced at accelerators and nuclear reactors. They are usually divided in long- and short-baseline, according to the distance between the neutrino production point and the detector.

Many short baseline accelerator experiments didn't find any signal of oscillation. They are nevertheless important, because they give constraints on the possible values of the mixing parameters. The most important limits have been obtained by NOMAD (20) and CHORUS (21) at CERN.

These two experiments were designed to check relatively high values of the mass differences ($\Delta m^2 \gtrsim 1 \text{ eV}^2$) and used a beam of ν_μ to look for a signal of a τ production, that would have been an indication of $\nu_\mu \rightarrow \nu_\tau$ oscillations .

Besides the long baseline reactor experiments it is worthwhile to recall the results of CHOOZ (22) and Palo Verde (23, 24). At CHOOZ a beam of reactor $\bar{\nu}_e$ was sent

to a detector located about 1 Km away and detected through the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. No evidence of oscillation was found at CHOOZ and the experimental result for R , that is the ratio between the number of measured $\bar{\nu}_e$ events and the expected number in absence of oscillation, is compatible with $R = 1$. In a simple two flavor model the oscillation probability is given by the relation

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \frac{1}{2} \sin^2 \theta \left(1 - \cos \left(2.53 \frac{\Delta m^2 L}{E} \right) \right) \quad (\alpha \neq \beta), \quad (2)$$

where L is the distance source-detector expressed in meters, E is the ν energy in MeV and Δm^2 is the difference of the squares of neutrino masses expressed in eV^2 . The range of mass differences and mixing angles that can be tested in a certain experiment is limited by the requirements that the source-detector distance be much shorter than the oscillation length

$$\left(L_{osc}(m) \simeq 2.48 \frac{E(\text{MeV})}{\Delta m^2(eV^2)} \right).$$

The CHOOZ average energy value is $\langle E \rangle \approx 3\text{MeV}$; therefore CHOOZ results can be used to exclude a significant part of the mixing parameters plane. In particular they tell us that Δm^2 must be smaller than $10^{-3}eV^2$, unless the values of the mixing angle are very small.

The opposite situation took place in the case of LSND ^{25, 26)}, a short baseline accelerator experiment performed with a neutrino beam produced at the Los Alamos meson physics facility (LAMPF). The experiment found evidence of two kinds of oscillation signals. The first was the excess of $\bar{\nu}_e$ in the beam of $\bar{\nu}_\mu$ produced by the decay at rest of the μ^+ obtained as secondary products of the proton accelerator beam. The second was a signal of $\nu_\mu \rightarrow \nu_e$ oscillations, starting from the ν_μ produced by the π^+ decay in flight. The LSND result, if confirmed, ought to be a clear indication of oscillation with very high values of the mass difference, up to $\Delta m^2 \geq 1eV^2$. To reconcile this result with the ones coming from solar and atmospheric neutrinos one would have to postulate the existence of at least one sterile neutrino in addition to the usual three active ones ¹. However, up to now there has been no independent confirmation of the LSND results. The KARMEN experiment ^{28, 29)}, performed at the Rutherford Laboratories, explored a significant part of the mixing parameter space proposed by LSND and it didn't find any signal of oscillation ². A new experiment MiniBoone ^{31, 32)} is going to run very soon and produce data

¹for a recent discussion about the possible explanations of LSND data see ²⁷⁾

²About the compatibility of LSND and Karmen results see also ³⁰⁾

starting from 2004. It is very similar to LSND and will test definitely the validity of LSND results.

A new generation of very long baseline experiments has become available in the last years. The forerunner of them is K2K (33–35), that uses a neutrino beam produced at the Japan kaon facility KEK and detected at the Kamioka site. Up to now K2K has detected 56 events instead of the expected value in absence of oscillations of $80_{-8}^{+7.3}$ events. This is a confirmation of neutrino oscillations (the no-oscillation probability is less than 1%). Moreover the best fit point (35) values for the mass difference and the mixing angle ($\Delta m^2 = 2.8 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1$) are in good agreement with the results of atmospheric neutrino experiments. Two similar projects have already been approved and will become available in the near future: one of them is a neutrino beam from CERN to the Gran Sasso Labs (36–39) and the other one is in the USA (40, 41) (from FNAL to Soudan). The long baseline accelerator experiments will probably give an important confirmation of the oscillation evidence which have up to now come from the study of solar and atmospheric neutrinos. They are also expected to find in an unambiguous way indications of oscillation from appearance signals. In addition, in the long baseline experiment one has the opportunity of choosing the specific characteristic of the beam; hence they can be used to perform precision measurements (42, 43). For instance they should be useful to study the value of the mixing angle θ_{13} , relevant for eventual CP violation. The present limit on the measurement of this angle coming from CHOOZ ($\theta_{13} \leq 9$ degrees), could be lowered to the level of about 5 degrees at ICARUS, one of the two experiments that will use the CERN-Gran Sasso beam.

Important results should very soon come from the long baseline reactor experiment KamLAND (44), which might in principle give a definite solution to the solar neutrino problem, as we will see in the following.

The two main categories of experiments looking for oscillation signals are the ones that study the atmospheric and the solar neutrinos. The atmospheric neutrinos are products of decay of the cosmic rays. The number of electronic and muonic neutrinos can be computed with good accuracy, considering the properties of cosmic rays, their decay channels and eventually geomagnetic effects. Most of the atmospheric neutrino experiments measure the value of the double ratio

$$R = \frac{(\mu/e)_{data}}{(\mu/e)_{MC}}.$$

The numerator and denominator are respectively the experimental and the Monte Carlo computed values of the ratio between the events generated by muonic neu-

trinos (and antineutrinos) and the ones generated by electronic neutrinos (antineutrinos). There are essentially two kind of experiments: the water Cherenkov (like Kamiokande ^{45–48}), Super-Kamiokande ^{49–53}, IMB ⁵⁴) and the iron plate calorimeters (like Soudan II ⁵⁵) and in the past years Frejus ^{56, 57}) and Nu-sex ^{58, 59}). Clear evidence of oscillations has been found at Kamiokande, Super-Kamiokande (SK), IMB and Soudan II and also at the MACRO ^{60, 61}) experiment at Gran Sasso. The best statistic has been obtained at SK, which found ⁵³) $R = 0.638 \pm 0.016 \pm 0.050$ for the Sub-GeV events and $R = 0.658_{-0.028}^{+0.030} \pm 0.078$ for the Multi-GeV events. Another interesting observable is the up-down asymmetry between the up going events, in which the neutrino crossed the Earth before interacting in the detector, and the down going ones: $A_{e,\mu} = \frac{U-D}{U+D}$. The experimental value of this quantity is consistent with zero for the electronic neutrinos, while for the muonic ones the up-down asymmetry for high values of the momenta is a decreasing negative value. These results are clear indications of a reduction of the flux of muonic neutrinos and antineutrinos that arrive at the detector after crossing the Earth. The most natural explanation of this phenomenon is the possibility that the muonic neutrinos oscillate into other flavors and the oscillation probability is greatly enhanced by the interaction with matter.

The last group of experiments is that of the experiments observing the neutrinos coming from the Sun. We will discuss them in detail in the rest of the paper.

2.1 History of the solar neutrino problem

The first experiment on solar neutrinos, Homestake ⁶²), started at the end of the '60s using the inverse β decay on chlorine $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$. The threshold energy was $E_{thr} \simeq 0.81\text{MeV}$, hence it was sensitive to the pep, ^7Be , ^8B and hep components of the solar neutrino flux. The results were really surprising, because Homestake found a deficit of the solar neutrino flux of more than 60% that predicted by the Solar Standard Model (SSM). The updated value of the ratio R , between the experimental results and the SSM prediction ⁶³), for the chlorine experiment is $R = 0.34 \pm 0.03$. This result raised fundamental questions: what happens to solar ν on their way to earth? Eventually, could the SSM be wrong?

The Homestake indication was confirmed by similar experiments, SAGE ⁶⁴) in Russia and GALLEX ⁶⁵) and later on GNO ⁶⁶) at the INFN Gran Sasso Labs, which used gallium instead of chlorine. The energy threshold is lower in the gallium experiments ($E_{thr} \simeq 233\text{keV}$) making them also sensitive to pp neutrinos, which are the main component of the solar neutrino flux. The updated gallium results

are 64–66):

$$\begin{aligned} R &= 0.60 \pm 0.05 \quad (SAGE) \\ R &= 0.58 \pm 0.05 \quad (GALLEX - GNO). \end{aligned} \tag{3}$$

This confirmation of Homestake results gave a strong support to the neutrino oscillation hypothesis and caused an increase of the interest for this problem. It could be a signal of *new physics*.

An essential improvement in the knowledge of solar neutrinos came with the advent of the water Cherenkov experiments, Kamiokande⁶⁷⁾ and Super-Kamiokande (SK)^{68, 69)}, that looked at the elastic scattering $\nu_e + e^- \rightarrow \nu_e + e^-$ and confirmed the existence of the “solar neutrino problem” with a very high statistic. In this experiments it was possible to know the direction of the incoming neutrino (by looking at the outgoing direction of the recoil electron) and also to study the energy and angular spectrum and the day night asymmetries. The energy threshold for these experiments was quite high (5 MeV for SK) and therefore they were sensitive only to the high energy component of the neutrino flux, that is 8B and hep neutrinos. Their results confirmed the existence of a deficit in the electron neutrinos reaching the detector. The SK result for the energy spectrum and the small values of the day-night asymmetries were also very important to put strong constraints on the possible values of the mixing parameters.

After the publication of SK data it was clear that there was a deficit of solar electron neutrinos reaching the Earth, with respect to the flux predicted by SSM. The oscillation hypothesis was considered the most plausible explanation of this phenomenon, but there were still different regions allowed by the experiments in the mixing parameter plane, as we will see in detail.

2.2 The post SNO situation

The real breakthrough was due to the SNO experiment that published its first data in 2001⁷⁰⁾. SNO is a deuterium Cherenkov detector designed to look simultaneously at three different reactions:

$$\begin{aligned} \nu_e + d &\rightarrow e^- + p + p \quad (\text{Charged Current}); \\ \nu_x + d &\rightarrow e^- + n + p \quad (\text{Neutral Current}); \\ \nu_x + e^- &\rightarrow \nu_x + e^- \quad (\text{Elastic Scattering}). \end{aligned} \tag{4}$$

The first reaction (CC) receives contribution only from the electron neutrino, while the others (NC and ES) are sensitive to all neutrino flavors. This experiment gives the first direct model independent measurement of the total solar neutrino flux

reaching the Earth (through the NC observation) and at the same time, comparing this flux with the one of ν_e recovered from CC, it offers a strong evidence of the oscillation of ν_e into other active neutrinos.

During its first phase of working ⁷⁰⁾ SNO observed the charged current and elastic scattering events, with an energy threshold for electron detection of 6.75 MeV. The ν_e flux measured from CC, after 241 days of running, was: $\Phi_{\nu_e}^{CC} = 1.75 \pm 0.07(stat.)_{-0.11}^{+0.12}(syst.) \times 10^6 cm^{-2}s^{-1}$. The ratio between this value and the SSM prediction was $R = 0.35 \pm 0.03$. In the SNO experiment the neutrino flux can be recovered also from the elastic scattering, using the relation ³⁾:

$$\Phi_{\nu}^{ES} = \Phi_{\nu_e}^{ES} + 0.154 \sum_{i=\mu,\tau} \Phi_{\nu_i}^{ES}. \quad (5)$$

The value of the total neutrino flux recovered from the elastic scattering at SNO and also, with a better statistics, at SK doesn't agree with the ν_e flux obtained from SNO CC. The comparison of the two results gives:

$$\sum_{i=\mu,\tau} \Phi_{\nu_i}^{ES} = 3.69 \pm 1.13 \times 10^6 cm^{-2}s^{-1}. \quad (6)$$

This result was the first evidence (at 3σ level) of the presence of muonic and tauonic neutrinos in a electronic neutrino beam reaching the Earth from the Sun. Therefore it was, up to the present SNO data on NC, the most robust evidence of ν_e oscillation into other active neutrinos. It is also remarkable that the sum of the ν_e and $\nu_{\mu,\tau}$ fluxes give a value in good agreement with the SSM prediction. Consequently the results of SNO phase I also strongly disfavored the hypothesis of pure oscillation into sterile neutrinos.

Recently, while this paper was in preparation, the data of the so called phase II of SNO also became available ^{71, 72)}. This data, obtained with 306.4 days of running, confirms the indications of the phase I and includes the first neutral currents (NC) observations.

3 Global analysis of the solar neutrino data

Given all the experimental data that we have just reported, one can say that there is really strong evidence that neutrinos are massive and oscillating particles. Nevertheless, many details of the mass patterns still have to be clarified. With this aim in

³⁾the contribution of ν_{μ} and ν_{τ} to the elastic scattering cross section is only through neutral current, hence it is about 1/6 of the contribution of ν_e that can interact also through charged current

mind, we developed a global analysis of all the available data on solar neutrinos, also including the CHOOZ constraints. Our first purpose was that of determining the regions in the mixing parameter plane that are still compatible with the experiments. In addition to this, we wanted to understand how the forthcoming experiments (in particular Borexino and KamLAND) could improve our knowledge of neutrino mass properties.

We assumed neutrino oscillation as a working hypothesis and considered bidimensional models. For details of our analysis we refer the interested reader to ^{73, 74}). Here we just report the most salient aspects of our strategy. The analysis is based on the numerical calculation of the expected event rate for every solar neutrino experiment as a function of the mixing parameters and on the comparison between these expected numbers and the experimental data. The statistical analysis is based on the χ^2 method its output being contour plots in which one can see which values of the mixing angles and mass differences are still allowed at a given confidence level.

Our calculation can essentially be split into two parts. The first one is the determination of the neutrino transition amplitude, i.e. the probability for an electronic neutrino produced in the Sun to change its flavor before reaching the detector. The other ingredient is the calculation of the detector response functions, that, for a given neutrino energy, depend on the experimental details of the specific detector (i.e. efficiency, resolution, etc.) and on the cross section for the reaction under examination.

The transition amplitude calculation is separated in three parts, corresponding to the neutrino propagation inside the Sun, in the vacuum and in the Earth. For every value of the mixing parameters we compute fully numerically the amplitudes in the Sun and in the Earth, while the one corresponding to the vacuum evolution is computed analytically. The three amplitudes are patched together using the evolution operator formalism ⁷⁵).

4 The present situation

We included in our analysis the total rates of the chlorine and gallium experiments, together with the different energy bins of SuperKamiokande and with the charged current results of the first phase of SNO. The resulting contour plots are reported in Figure 1. One can note that there are still two allowed region, even at 90% C.L.: the Large Mixing Angle (LMA), where we found the best fit point with a goodness of fit (g.o.f.) of 84.38%, and the so called LOW solution, characterized by lower values of the mass differences. The two other possible solutions of the solar neutrino

problem, that historically have been considered, are the Small Mixing Angle (SMA) and the vacuum solution, corresponding to much lower values of Δm^2 . These two solutions cannot be completely excluded, even if they are strongly disfavored mainly by SK data on the day and night energy spectrum and by the SNO results. Another effect of SNO data was that of shrinking the different regions which became well separated. Our results are in good agreement with most of the analysis one could find in literature (76).

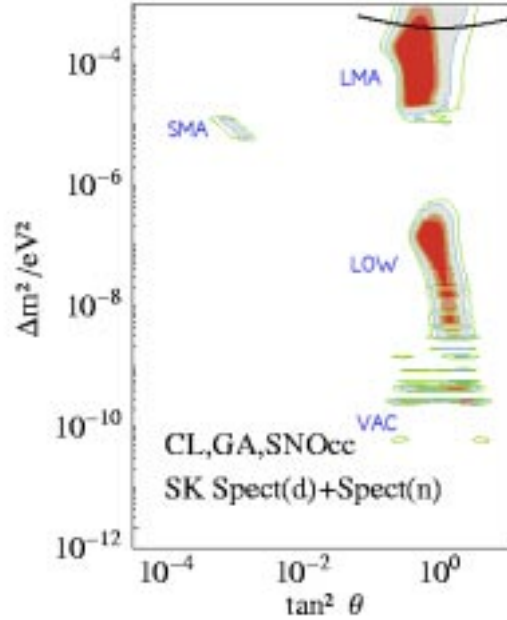


Figure 1: *The situation after the charged current SNO data. The different colored regions correspond to different confidence levels: 90%, 95%, 99% and 99.7%.*

5 Future scenarios

Given this situation, we studied which new information should come in future from the Borexino data (77, 78). Borexino (79, 80) is a solar neutrino experiment, mainly sensitive to the ${}^7\text{Be}$ component of the neutrino flux, that should start running in very next years at the Gran Sasso Labs. In Figure 2 the usual contour plots obtained from all the experiments available up to now are superimposed to the contour lines corresponding to different hypothetical possible values of the total rate at Borexino. As one can see from the picture, Borexino should be able to clarify the situation in the case in which the solution very well is in the small mixing angle region. The situation would be, instead, more complicate in case of LMA or

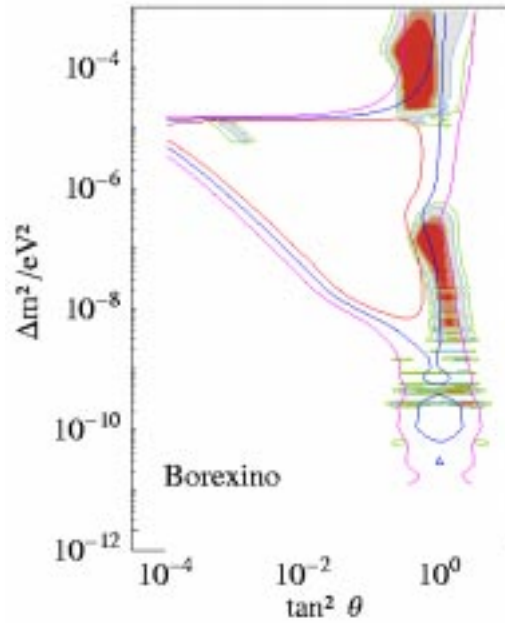


Figure 2: *Possible values of the total signal at Borexino. The full lines correspond to a total rate equal respectively to 0.5, 0.6 and 0.7 with respect to the SSM prediction in absence of oscillation. These isosignal lines are superimposed to the contour plots (colored regions) corresponding to the regions allowed at different confidence levels from the other experiments.*

LOW solutions. In these two regions, in fact, the ratio between the Borexino signal and the SSM prediction in absence of oscillations should be between 0.6 and 0.7 . The discrimination power of Borexino increases a lot if we look also at the day-night asymmetry, as one can see from Figure 3. The LOW region is characterized by high values of the asymmetry, that can reach up to 20%, while in the LMA region the day-night asymmetry is much lower. Hence, by looking simultaneously at the total rate and at the day-night asymmetry, Borexino should be able to discriminate between the two solutions of the solar neutrino problem that are compatible with the experiments up to now, that is the LMA and the LOW solutions.

Another very important experiment, already running, that should significantly improve our knowledge of the mixing parameters relevant for solar neutrinos is KamLAND ⁴⁴). In this experiment a flux of low energy $\bar{\nu}_e$ produced by different nuclear reactors is sent to a scintillator detector capable of detecting their interactions with protons. Although it is not a traditional solar neutrino experiment, KamLAND is sensitive to neutrino oscillations with mixing parameters in the LMA region, that

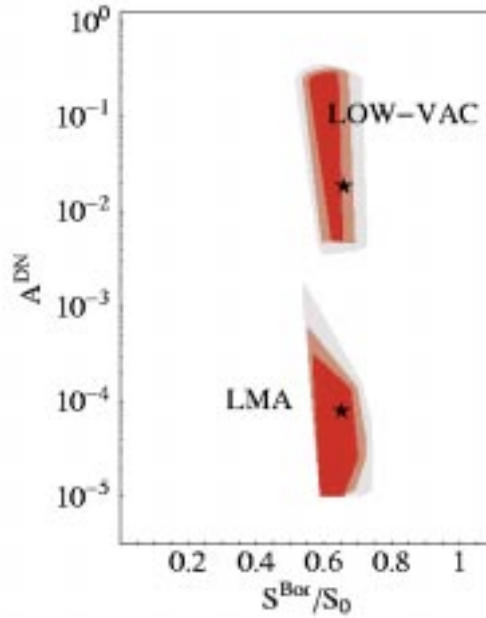


Figure 3: *Predicted values of the day-night asymmetry at Borexino.*

seems to be the solution of the solar neutrino problem preferred by the present data. Therefore, we can hope that KamLAND will soon be able to determine the exact values of the mixing parameters with satisfactory accuracy. The main limitation of KamLAND is its reduced sensitivity to the extreme upper part of the LMA region, that could create problems in the determination of Δm_{12}^2 , as discussed in (81) and later on in (82). For a detailed discussion about KamLAND potentiality and discrimination power we refer the interested reader to (77).

While this paper was in preparation the data of the second phase of SNO was published (71, 72). They contained the first direct observation of the neutral current (NC) process and the data of the CC and ES processes with statistics higher than the one the first SNO phase (70). From the NC data one can recover a value of the total active flux $\Phi_{8B}^{NC}(\nu_{TOT}) = 5.09_{-0.43}^{+0.44}(syst.)_{-0.43}^{+0.46}(stat.)$ which is in very good agreement with the SSM prediction ($\Phi_{8B}(\nu_e) = 5.05 \times 10^6 cm^{-2} s^{-1}$, if we use the old value for S_{17}). This result is an important confirmation of the validity of the SSM. At the same time, comparing these values with the SK and SNO ES values of the $8B$ electron neutrino flux one obtains proof that a significant part of the electron neutrinos coming from the Sun is converted into other active flavors (there is a 5.3σ evidence that the flux of $\nu_{\mu,\tau}$ is different from zero).

We have redone our analysis with the addition of these recent SNO data. In (74) we have assumed the simplifying hypothesis that the spectrum is undistorted with

respect to the form predicted by the SSM in absence of oscillations. This assumption is essentially valid in the LMA region (the one preferred by the data at the moment). For the detailed values of the mixing parameters we recovered in this region and for the related study of KamLAND potentiality we refer the reader to ⁷⁴⁾. Here we just recall that our results are in good agreement with other similar analysis ⁸⁴⁾. We are also doing a more sophisticated analysis of the full mixing parameter plane, without the undistorted spectrum hypothesis and any other model dependent assumption.

A critical analysis of the influence of the different experimental results and of the possible experiments that should come after Borexino and KamLAND is performed, for instance, in ⁸⁵⁾

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