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Random matter density perturbations and LMA

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Abstract. There are reasons to believe that mechanisms exist in the solar interior which lead to random density perturbations in the resonant region of the Large Mixing Angle solution to the solar neutrino problem. We find that, in the presence of these density perturbations, the best fit point in the $(\sin^2 2\theta, \Delta m^2)$ parameter space moves to smaller values, compared with the values obtained for the standard LMA solution. Combining solar data with KamLAND results, we find a new compatibility region, which we call VERY-LOW LMA, where $\sin^2 2\theta \approx 0.6$ and $\Delta m^2 \approx 2 \times 10^{-5}$ eV^2, for random density fluctuations of order $5\% < \xi < 8\%$. We argue that such values of density fluctuations are still allowed by helioseismological observations at small scales of order 10 - 1000 km deep inside the solar core.

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Assuming CPT invariance, the electronic antineutrino $\bar{\nu}_e$ disappearance as well as the neutrino energy spectrum observed in KamLAND [1] are compatible with the predictions based on the Large Mixing Angle (LMA) realization of the MSW mechanism, resonantly enhanced oscillations in matter [2,3]. This compatibility makes LMA the best solution to the solar neutrino anomaly [4]-[10]. The best fit values of the relevant neutrino parameters which generate such a solution are $\Delta m^2 = 7.3 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.41$ with a free boron neutrino flux $f_B = 1.05$ [11] with the 1 σ intervals: $\Delta m^2 = (6.2 \leftrightarrow 8.4) \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.33 \leftrightarrow 0.54$.

Such an agreement of the LMA MSW predictions with the solar neutrino data is achieved assuming the standard approximately exponentially decaying solar matter distribution [12]-[14]. This prediction to the matter distribution inside the sun is very robust since it is in good agreement with helioseismology observations [15].

There are reasons to believe, nevertheless, that the solar matter density fluctuates around an equilibrium profile. Ideed, in the hydrodynamical approximation, density perturbations can be induced by temperature T fluctuations due to convection of matter between layers with different temperatures. Considering a Boltzman distribution for the matter density, the density fluctuations are found to be around 5% [16]. Another estimation of the level of density perturbations in the solar interior can be given considering the continuity equation up to first order in density and velocity perturbations and the p-modes observations. This analysis leads to a value of density fluctuation around 0.3% [17].

The mechanism that might produce such density fluctuations can also be associated with modes excited by turbulent stress in the convective zone [18] or by a resonance between g-modes and magnetic Alfvèn waves [19]. As the g-modes occur within the solar radiative zone, these resonance creates spikes at specific radii within the Sun. It is not expected that these resonances alter the helioseismic analyses because as they occur deep inside the Sun, they do not affect substantially the observed p-modes.

This resonance depends on the density profile and on the solar magnetic field, and as mentioned in [19], for a magnetic field of order of 10 kG the spacing between the spikes is around 100 km. In the analyses presented in [19] the values considered for the magnetic field are the ones that satisfy the Chandrasekar limit, which states that the magnetic field energy must be less than the gravitational binding energy.

Considering helioseismology, there are constraints on the density fluctuations, but only those which vary over very long scales, much greater than 1000 km [20–22]. In particular, the measured spectrum of helioseismic waves is largely insensitive to the existence of density variations whose wavelength is short enough - on scales close to 100 km, deep inside within the solar core - to be of interest for neutrino oscillation, and the amplitude of these perturbations could be large as 10% [19].

So, there is no reason to exclude density perturbations at a few percent level and there are theoretical indications that they really exist.

In the present paper [23], we study the effect on the Large Mixing Angle parameters when the density matter

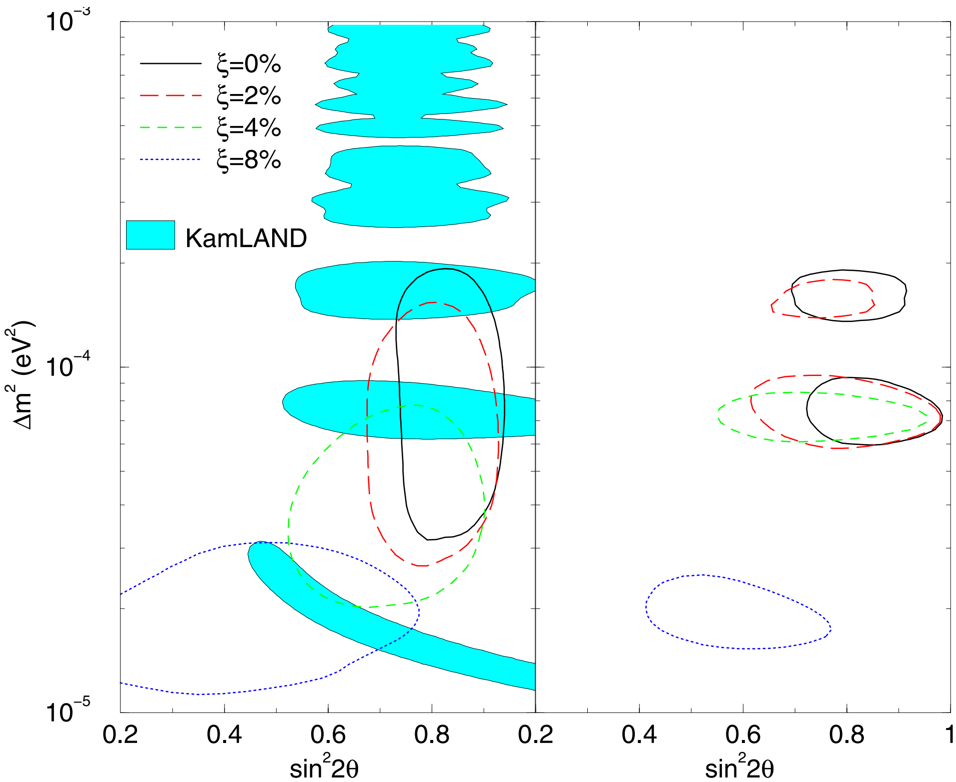

Fig. 1. LMA region for different values of the perturbation amplitude, at 95% C.L. for several values of the perturbation amplitude, $\xi = 0\%$ (*solid line*), for $\xi = 2\%$ (*long dashed line*), $\xi = 4\%$ (*dashed line*) and $\xi = 8\%$ (*dotted line*). We also present the allowed region for KamLAND spectral data, for the same C.L. In the right-handed side of the figure, the combined analysis of both solar neutrino and KamLAND observations is shown

fluctuates around the equilibrium profile. This is a reasonable case, considering that in the lower frequency part of the Fourier spectrum, the p-modes resembles that of noise [16]. Also, considering the resonance of g-modes with Alfvén waves, the superposition of several different modes results in a series of relatively sharp spikes in the radial density profile. The neutrino passing through these spikes fell them as a noisy perturbation whose correlation length is the spacing between the density spikes [19].

References [16] and [25] have analyzed the effect of a matter density noise on the MSW effect and found that the presence of noisy matter fluctuations weakens the MSW mechanism, thus reducing the resonant conversion probabilities. These papers, nevertheless, did not take into consideration KamLAND data.

In order to analyze the effect of a noisy density on the neutrino observations, we must consider the evolution equations for the neutrino when the density is given by a main average profile perturbed by a random noisy fluctuation. This is done starting from the standard Schrödinger equation [24,16]. We calculate the survival probability of the neutrinos solving the evolution equation [23], considering the equilibrium density profile given by the Standard Solar Model [14].

In Fig. 1 we present the $(\sin^2 2\theta, \Delta m^2)$ parameter space comparing the results obtained for solar neutrinos with the allowed regions obtained from KamLAND observations, for four values of density perturbation, $\xi = 0\%, 2\%, 4\%$ and 8%. We observe that the values of the parameters Δm^2 and $\sin^2 2\theta$ that satisfy both the solar neutrinos and KamLAND observations are shifted in the direction of lower values of Δm^2 and $\sin^2 2\theta$ as the amplitude of the density noise increases. In the left-handed side of Fig. 1, the best fit point of the solar analysis with no perturbations lies in $(\sin^2 2\theta, \Delta m^2) = (0.82, 7.2 \times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 65.4$. For $\xi = 4\%$, the best fit point goes to $(\sin^2 2\theta, \Delta m^2) = (0.71, 3.5\times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 64.0$, while for $\xi = 8\%$ we have $(\sin^2 2\theta, \Delta m^2) = (0.33, 1.4 \times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 64.2$. The numbers of degrees of freedom (d.o.f.) in this analysis is 78, obtained from 81 data points, 2 oscillation parameters and ξ.

The right-handed side of Fig. 1 shows the combined analysis involving both solar neutrino and KamLAND data. The best fit point of this analysis when no perturbations is assumed lies in $(\sin^2 2\theta, \Delta m^2) = (0.85, 7.2 \times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 71.1$. For $\xi = 4\%$, our best fit point goes to $(\sin^2 2\theta, \Delta m^2) = (0.81, 7.2 \times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 71.5$, while for $\xi = 8\%$ we have $(\sin^2 2\theta, \Delta m^2) = (0.52, 1.9 \times 10^{-5}\mathrm{eV}^2)$, with a minimum $\chi^2 = 75.5$. Here, the number of d.o.f. is 91 .

!l The main consequence of introducing random perturbation in the solar matter density is the appearance of entirely new regions in the ($\sin^2 2\theta \times \Delta m^2$) which allow simultaneous compatibility of solar neutrino data and KamLAND observations. Besides the two standard LMA regions, shown in the right-handed side of Fig. 1 by the continuous lines, which were called high and low-LMA in [11], we find a new region displaced toward smaller values of $\sin^2 2\theta$ and Δm^2 which we call VERY-low-LMA. There $\Delta m^2 = (1 \leftrightarrow 3) \times 10^{-5}$ eV^2 and $\sin^2 2\theta = (0.4 \leftrightarrow 0.8)$, at 95% C.L., obtained for $\xi = 8\%$.

This represents a challenge for the near future confront of solar neutrino data and high-statistic KamLAND observations. If KamLAND will determine $\sin^2 2\theta < 0.5$ and $\Delta m^2 < 4 \times 10^{-5}$ eV^2 it can be necessary to invoke random perturbations in the Sun to recover compatibility with solar neutrino observations.

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