Non-standard interactions and Sterile Neutrino from Solar data

C.R. Das

The Bogoliubov Laboratory of Theoretical Physics (BLTP)
The Joint Institute for Nuclear Research (JINR)
Joliot-Curie 6, 141980 Dubna, Moscow region, Russia

Abstract

The flatness of the SuperKamiokande neutrino electron scattering spectrum and the apparent downturn of the charged current spectrum in the SNO data which the Large Mixing Angle solution (LMA) to the solar neutrino problem fails to predict are analysed in the context of an extension to the standard electroweak model with light sterile neutrinos. It is found that a sterile neutrino which is quasi degenerate with the active ones with $\Delta m^2_{41} = 10^{-5} eV^2$ and mixing $sin\theta_{14} = 0.04$ provides a suitable improvement to the LMA data fits.

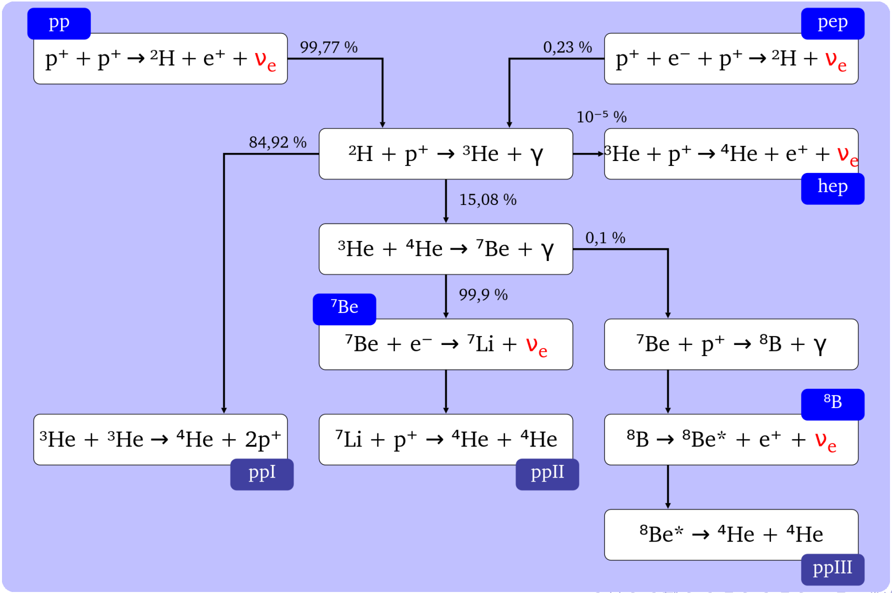
Eye is better than χ.

— Boris Kayser

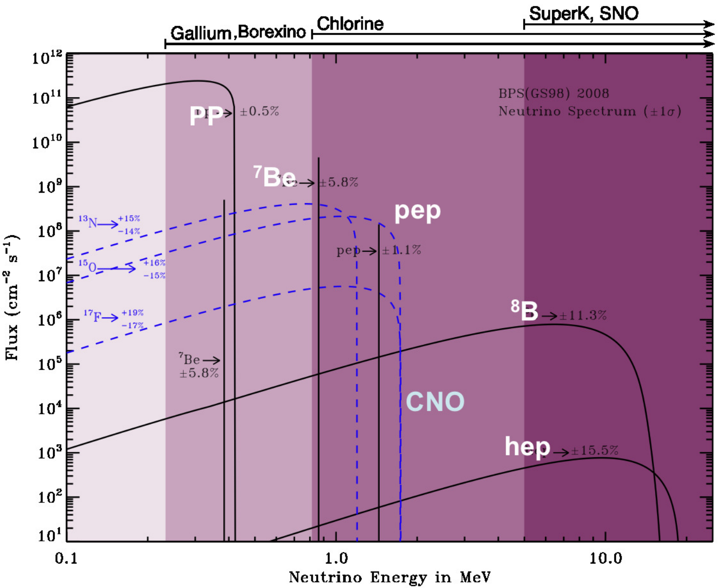
Both eyes are better than χ^2.

— Myself

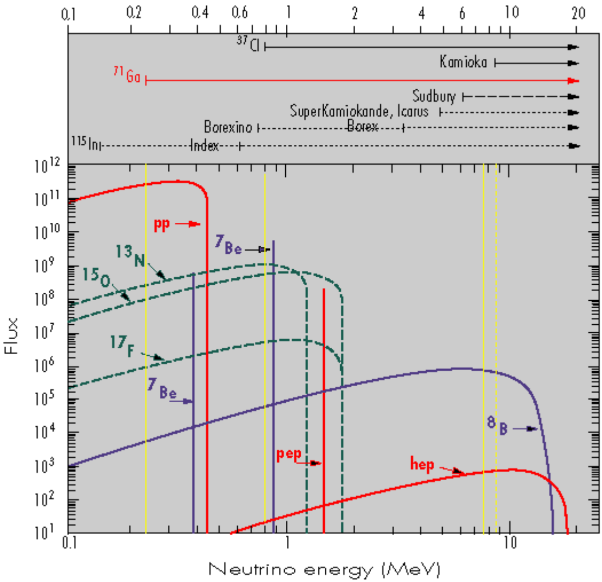
Solar Neutrino



Solar Neutrino



Solar Neutrino



Introduction

3+s neutrino schemes were introduced some time ago to account for anomalies occurring in very short baseline experiments ($L \sim \mathrm{few} \times 10m$): the accelerator (LSND, KARMEN, ICARUS, MiniBooNE), reactor and Gallium anomalies.
A short oscillation length is needed, implying an oscillation to one or two sterile states (s=1 or 2) with

$$\Delta m_{41}^2,\ \Delta m_{51}^2 = O(|1eV^2|).$$

Leading terms (one sterile only):

- Neutrino appearance (accelerator experiments):

$$P_{\nu_\mu \to \nu_e} = 4 sin^2 \frac{\Delta m_{41}^2}{4E} L |u_{e4}|^2 |u_{\mu 4}|^2$$

- Neutrino disappearance
  (reactor experiments + Gallium calibration):

$$P_{\nu_e \to \nu_e} = 1 - 4 sin^2 \frac{\Delta m_{41}^2}{4E} L |u_{e4}|^2 (1 - |u_{e4}|^2)$$

Introduction

Limits are given in the literature in terms of 'effective' angles:

$$sin^2 2\theta_{e\mu} = 4|u_{e4}|^2|u_{\mu 4}|^2, \; sin^2 2\theta_{ee} = 4|u_{e4}|^2(1 - |u_{e4}|^2)$$

- $sin^2 2\theta_{e\mu} = (4 - 10) \times 10^{-3}$

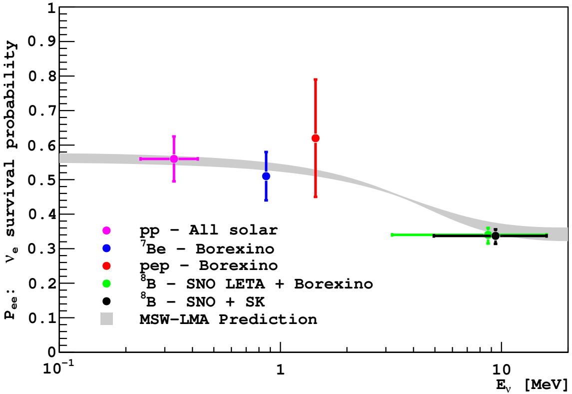
  $\Delta m^2 = (4 - 7) \times 10^{-1} eV^2$ (accelerator)

- $sin^2 2\theta_{ee} = (70 - 200) \times 10^{-3}$

  $\Delta m^2 = (2 - 3) eV^2$ (reactor, Ga)

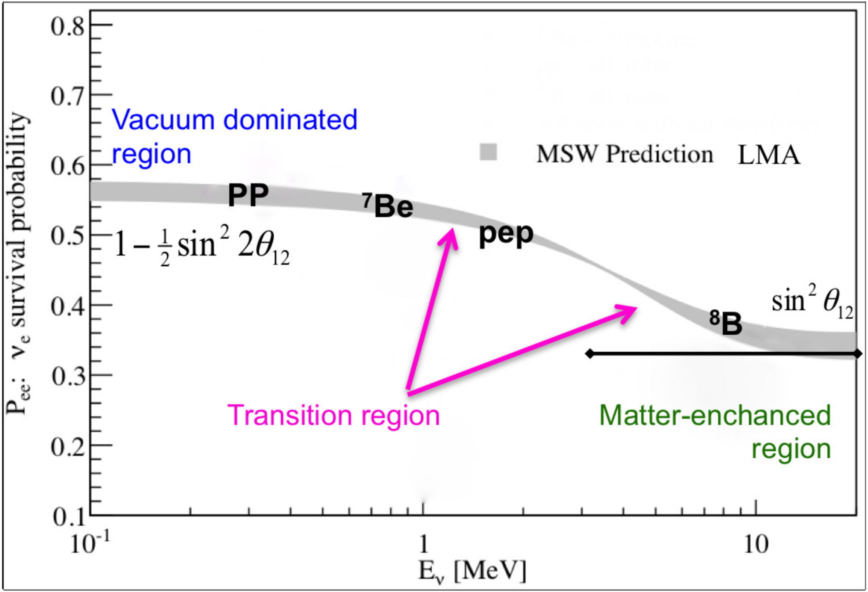
Introduction

Common prejudice asserts that the solar neutrino problem is by now 'solved' which is not the case. In fact an estimation made by the Borexino Collaboration shows that there is a gap in the knowledge of the neutrino survival probability in the vacuum matter transition region.

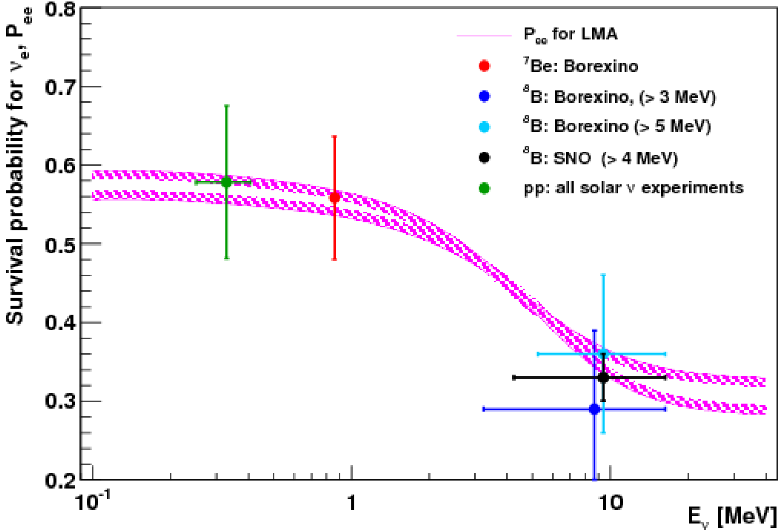


Borexino Collaboration, Phys. Rev. Lett. **108**, 051302 (2012).

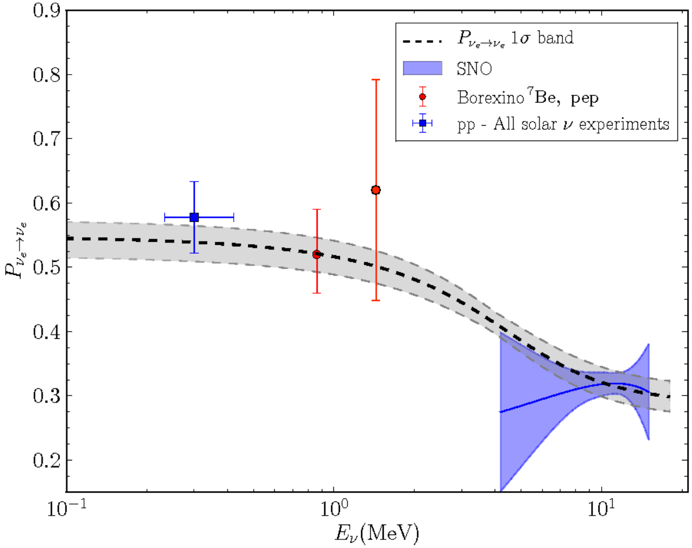
Introduction



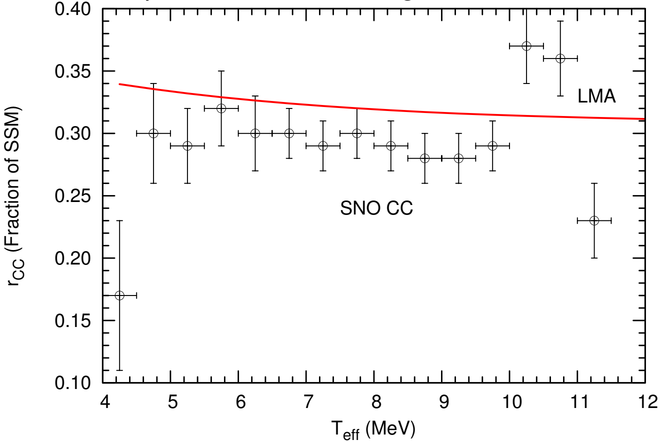
Introduction



Introduction



Moreover, besides the long standing problem of the flatness of the SK spectrum which LMA fails to explain, also the LMA CC spectrum prediction seems to proceed in the wrong direction.



This lead us to investigate different shapes of the neutrino survival probability from the LMA one.

The Model

- Hence: introduce light sterile neutrinos and investigate possible ranges of Δm^2_{new}, θ_{new}. Adequate shapes for probability were found with sterile neutrinos which are quasi degenerate with respect to the active ones, ($\Delta m^2_{new} = O(10^{-5} eV^2)$) with small mixing to these.

- So they are different from the 'conventional' steriles that are suggested by accelerator, reactor and Ga anomalies.

- The latter do not play any major role in solar neutrino oscillations.

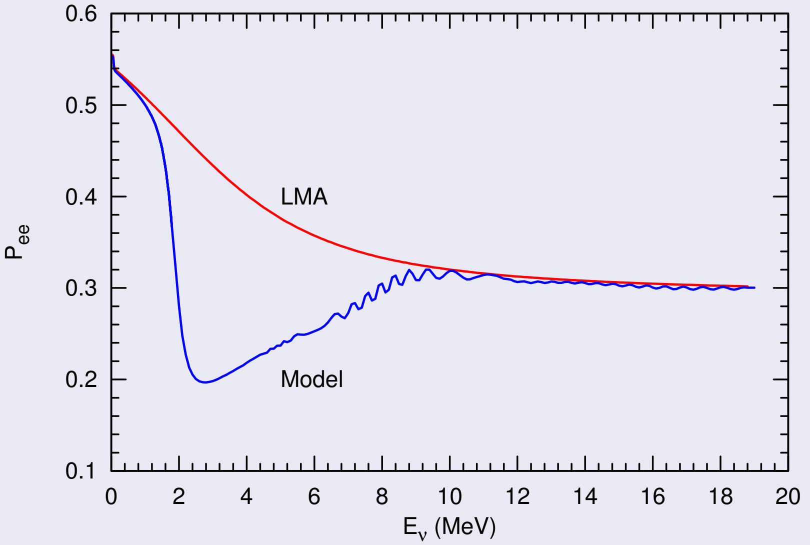
The Model

Our 4×4 Hamiltonian describing the solar neutrino oscillations is in the weak basis

$$(H_I)_W = U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -V_{NC} \end{pmatrix}$$

where U is the straightforward 4×4 extension of the usual leptonic mixing matrix, $V_{CC} = G_F\sqrt{2}N_e$, $V_{NC} = -G_F/\sqrt{2}N_n$ with $N_e,\ N_n$ denoting the electron and neutron densities. We use the representation $U = U_{34}\tilde{U}_{24}\tilde{U}_{14}U_{23}\tilde{U}_{13}U_{12}$. At this early stage of sterile neutrino investigation for the solar case we assume all sterile mixings to be equal with $sin\theta_{41} = 0.04$.

The Model



The Model

CC spectrum (reduced rate):

As for the relevant physical quantities, we start with the SNO CC spectrum evaluated as

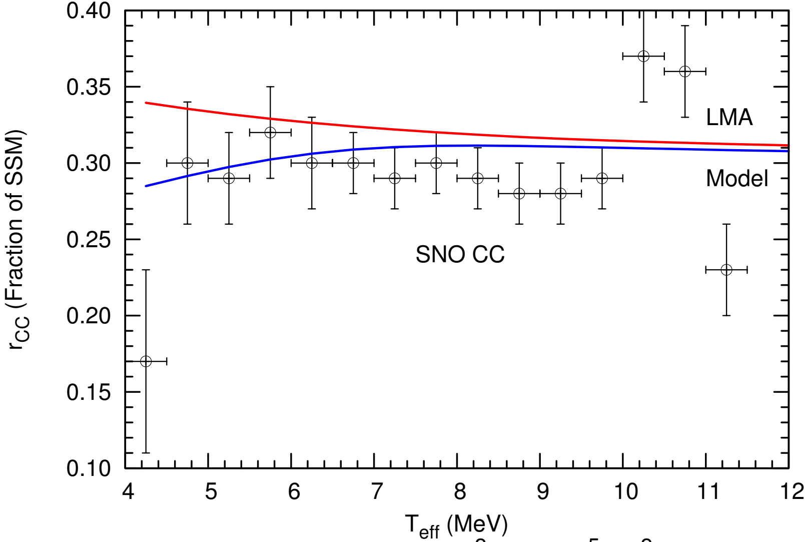
$$R_{CC}(T_{eff}) = \frac{\int_{Q}^{E_{max}} \frac{d\phi_{\nu}(E)}{dE} P(E) \int_{m_e}^{E-(Q-m_e)} R(T_{eff}, T) \frac{d\sigma_{CC}}{dT_{eff}} dT dE}{P(E) \to 1}$$

where $Q = 1.442\ MeV$ and T, T_{eff} are the physical and measured kinetic energy of the electron. $R(T_{eff}, T)$ is the energy resolution function and the rest of the notation is standard.

For the solar neutrino fluxes we used the AGSS09ph model. (John Bahcall home page -Institute for Advanced Study)

The Model

CC spectrum (reduced rate):



Neutrino parameters $sin\theta_{14} = 0.04, \ \Delta m^2_{41} = 10^{-5} eV^2$.

The Model

We have also evaluated the electron scattering spectrum (ES) for SNO, SK and Borexino from the expression

$$R_{ES}(E_{eff}) = \frac{\int_{m_e}^{E_{e\,max}} dE_e\ R(E_{eff}, E_e) \int_{E_m}^{E_M} dE \phi_\nu(E) \left[P_{ee}(E) \frac{d\sigma_e}{dE_e} + (P_{e\mu}(E) + P_{e\tau}(E)) \frac{d\sigma_{\mu,\tau}}{dE_e} \right]}{\int_{m_e}^{E_{e\,max}} dE_e\ R(E_{eff}, E_e) \int_{E_m}^{E_M} dE \phi_\nu(E) \frac{d\sigma_e}{dE_e}}$$

where E, E_{eff} are the physical and measured electron energy.

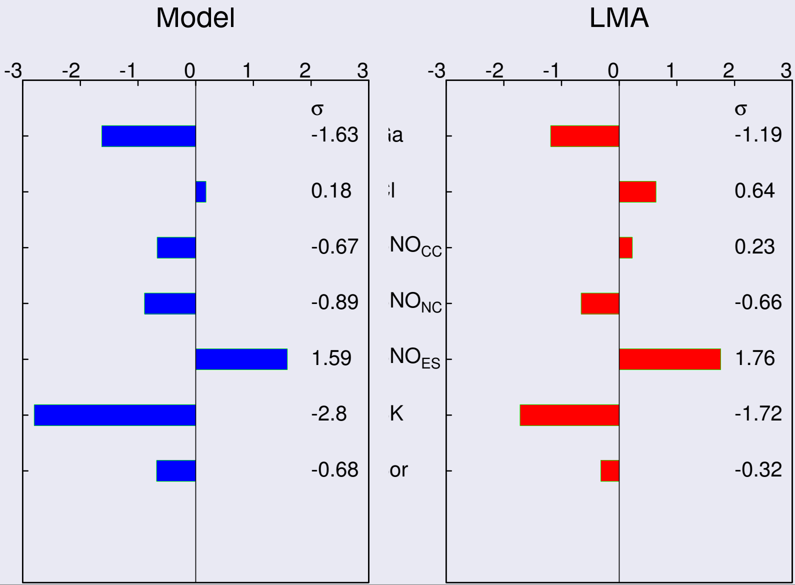
Other model predictions:

Rates

	$Ga(All, \leq Dec.2007)$ (SNU)	Cl (SNU)	$SNO(CC)$ $(\times 10^6\ cm^2 s^{-1})$	$SNO(NC)$ $(\times 10^6\ cm^2 s^{-1})$	$SNO(ES)$ $(\times 10^6\ cm^2 s^{-1})$	SK $(\times 10^6\ cm^2 s^{-1})$	$Borexino$ $(\times 10^6\ cm^2 s^{-1})$
Data	66.1 $\pm$3.1	2.56 $\pm$0.16 $\pm$0.15	1.67 $\pm^{0.05}_{0.04}$ $\pm^{0.07}_{0.08}$	5.54 $\pm^{0.33}_{0.31}$ $\pm^{0.36}_{0.34}$	1.77 $\pm^{0.24}_{0.21}$ $\pm^{0.09}_{0.10}$	2.32 $\pm$0.04 $\pm$0.05	2.40 $\pm$0.4 $\pm$0.1
LMA	62.4	2.70	1.69	5.22	2.21	2.21	2.27
Model	61.0	2.60	1.61	5.13	2.14	2.14	2.12

We use for SSM AGSS09ph (arXiv: 0910.3690).

The Model


Model
LMA
-3
-2
-1
0
1
2
3
σ
-1.63
0.18
-0.67
-0.89
1.59
-2.8
-0.68
ia
l
NOCC
NONC
NOES
K
or
-1.19
0.64
0.23
-0.66
1.76
-1.72
-0.32

Discussion

We next perform an analysis of the quality of the fits to the data. Using the standard χ^2 definition

$$\chi^2 = \sum_{j_1,j_2} (R_{j_1}^{th} - R_{j_1}{}^{\exp}) \left[\sigma^2(tot)\right]_{j_1 j_2}^{-1} (R_{j_2}^{th} - R_{j_2}{}^{\exp})$$

where indices j_1, j_2 run over the 7 solar neutrino experiments and the error matrix includes the cross section, the astrophysical and the experimental uncertainties, we obtain for the rates only, with $\Delta m^2_{sterile}$ and $\theta_{sterile}$ as free parameters.

Discussion

$$\chi^2_{rates}(LMA) = 8.1/5\ d.o.f.$$
$$\chi^2_{rates}(model) = 16.0/5\ d.o.f.$$

Two Caveats:

1. Contribution from Ga rate in χ^2 is extremely large: had we taken Ga/GNO data from the period 1998/03 ($62.9 \pm 5.4 \pm 2.5$ SNU) the result would be:

$$\chi^2_{rates}(LMA) = 3.6/5\ d.o.f.$$

$$\chi^2_{rates}(model) = 9.4/5\ d.o.f.$$

So χ^2_{rates} strongly depends on the Ga data period one considers.

Discussion

2. Moreover Ga rate has been decreasing all along the period of data taking:

GallexI	$\leq$ *June* 1992	83 ± 19
GallexII	*Aug*′92 $\rightarrow$ *Jun*′94	76 ± 10
GallexIII	*Oct*′94 $\rightarrow$ *Oct*′95	54 ± 11

	1991 – 97	1998 – 03
Gallex/GNO	$77.5 \pm 6.2 \pm^{4.3}_{4.7}$	$62.9 \pm 5.4 \pm 2.5$
SAGE	$79.2 \pm 8.6 \pm^{4.3}_{4.7}$	63.9 ± 5.0

	2003	2004	2005	2006	2007
SAGE	60 ± 10	72.5 ± 12.5	53 ± 9	68 ± 10	58.5 ± 8.5

This is suggestive that Ga could preferably be removed from χ^2_{rates} calculation.

Discussion

If we do so:

$$\Rightarrow \ \chi^2_{rates}(LMA) = 4.1/4 \ d.o.f. \ \ \text{(no Ga)}$$

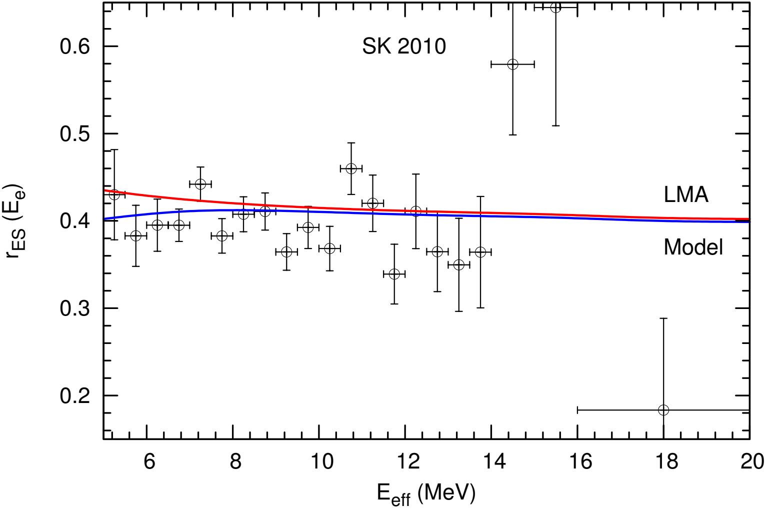
$$\chi^2_{rates}(model) = 3.7/4 \ d.o.f. \ \ \text{(no Ga)}$$

which shows an improvement in the rates fitting
(LMA$\rightarrow$ sterile ν model):

$$\chi^2_{rates}(model) < \chi^2_{rates}(LMA)$$

Discussion

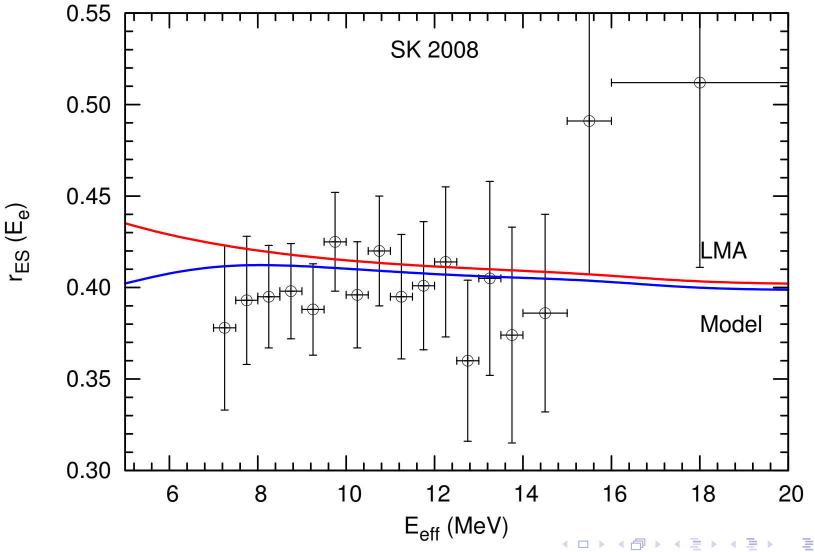
ES spectrum (reduced rate):



$\chi^2_{ES\ spectrum}(LMA) = 19.2/16 d.o.f.,\ \chi^2_{ES\ spectrum}(model) = 19.5/16 d.o.f.$

Discussion

If we resort to SK 2008 data the result seems more favourable:



Discussion

Recalling charged current (CC) reduced rate:

$$\chi^2_{CC\ spectrum}(LMA) = 24.3/13\ d.o.f.$$

$$\chi^2_{CC\ spectrum}(model) = 21.6/13\ d.o.f.$$

Discussion

χ^2 analysis for both SK data sets

For the 2010 data:

$$\chi^2_{\text{ES spectrum}}(\text{LMA}) = 19.2/16 \text{ d.o.f.} \quad , \quad \chi^2_{\text{ES spectrum}}(\text{model}) = 19.5/16 \text{ d.o.f}$$

For the 2008 data:

$$\chi^2_{\text{ES spectrum}}(\text{LMA}) = 3.6/12 \text{ d.o.f.} \quad , \quad \chi^2_{\text{ES spectrum}}(\text{model}) = 2.6/12 \text{ d.o.f}$$

Conclusions

- We still need to fill the gap in our knowledge of the solar neutrino survival probability in the intermediate energy region (i.e. the vacuum matter transition).
- LMA prediction for CC spectrum seems to point in the wrong direction as T_{eff} decreases.
- LMA provides no clue as to why SK spectrum is flat.
- Oscillations to sterile $\nu's$ which are almost degenerate with the active ones ($\Delta m^2 = 10^{-5} eV^2$, $sin\theta_{14} = 0.04$) lead to a CC spectrum pointing in the right direction and explain the flatness of the SK spectrum.
- We would be in presence of a 5th or 6th sterile neutrino. This would add to the already confusing situation concerning the sterile neutrinos.
- However as an example, the story of neutrino oscillations reminds us that a confusing picture at the start may eventually emerge, after an accumulation of experimental tests for several years, as a clear and positive one.

Sterile neutrino in supernova core-collapse model

We have experience in neutrino nonstandard interactions in the supernova. Neutrino nonstandard interactions (NSI) were investigated earlier in the solar case and were shown to reduce the tensions between the data and the large mixing angle solution predictions. We extend the previous framework to the supernova and evaluate the appearance probabilities for neutrinos and antineutrinos as a function of their energy after leaving the collapsing star with and without NSI. For normal hierarchy the probability for electron neutrinos and antineutrinos at low energy ($E \lesssim 0.8 - 0.9$ MeV) is substantially increased with respect to the non-NSI case and joins its value for inverse hierarchy which is constant with energy. Also for inverse hierarchy the NSI and non-NSI probabilities are the same for each neutrino and antineutrino species. Although detection in such a low energy range remains at present an experimental challenge, it will become a visible trace of NSI with normal hierarchy if they exist.

Sterile neutrino in supernova core-collapse model

On the other hand the neutrino decay probability into an antineutrino and a majoron, an effect previously shown to be induced by dense matter, is, as in the case of the sun, too small to be observed as a direct consequence of NSI. We will extent our investigation to sterile neutrino in supernova core-collapse model.

Despite significant advancements in modeling core-collapse supernovae, there are still phenomena that we do not understand. The existence of a right-handed sterile neutrino may provide a means of solving some of the issues related to the lepton fraction, neutrino spectrum and energy transport within the collapsing core. Sterile neutrinos could augment core collapse supernova shock energies by enhancing energy transport from the core to the vicinity of the shock front. The decay of these neutrinos could produce a flux of very energetic active neutrinos, detectable by future neutrino observations from a galactic supernova.

Sterile neutrino in supernova core-collapse model

The relevant range of sterile neutrino masses and mixing angles can be probed in future laboratory experiments. The presence of sterile neutrinos can affect the conditions for heavy-element formation in the supernova. We will examine how strongly active-sterile flavor conversion suppresses neutrino heating at times when it is important for the revival of the shock. Our results may suggest simulations of supernova explosion and nucleosynthesis to be used to constrain active-sterile mixing parameters in combination with neutrino experiments and cosmological considerations. We will also find sterile neutrino transport-enhanced entropy deposition ahead of the shock. Results may show that a few milliseconds prior to the core bounce there is a coherent conversion of electron neutrinos to sterile ones. This alters the neutrino spectrum and dynamics of the core collapse. People are investigating for light and heavy sterile neutrinos in supernovae, but not for ultra-light sterile neutrinos, which we observed in solar data.

Cosmology and sterile neutrino

The connection between cosmological observations and neutrino physics is one of the most interesting and hot topics in astroparticle physics. Sterile neutrinos are also candidates for dark radiation. The number of neutrinos and the masses of the particles can have large-scale effects that shape the appearance of the Cosmic microwave background (CMB). The total number of neutrino species, for instance, affects the rate at which the cosmos expanded in its earliest epochs: more neutrinos means a faster expansion. New measurements of the CMB by the Planck mission have greatly increased our knowledge about the universe. Dark radiation, a weakly interacting component of radiation, is one of the important ingredients in our cosmological model which is testable by Planck and other observational probes.

Cosmology and sterile neutrino

At the moment, the possible existence of dark radiation is an unsolved question. For instance, the discrepancy between the value of the Hubble constant H0 , inferred from the Planck data and local measurements of H0 can to some extent be alleviated by enlarging the minimal ΛCDM model to include additional relativistic degrees of freedom. From a fundamental physics point of view, dark radiation is no less interesting. Indeed, it could well be one of the most accessible windows to physics beyond the standard model, for example, sterile neutrinos. Also the new measurements of the CMB anisotropies released from the Planck collaboration, allow to place new and more stringent limits on the presence of extra relativistic species at the decoupling epoch. The CMB results from the Planck satellite, combined with previous CMB data and Hubble constant measurements from the Hubble Space Telescope, provide a constraint on the effective number of relativistic degrees of freedom 3.62 + 0.50 0.48 at 95% CL.

Cosmology and sterile neutrino

New Planck data provide a unique opportunity to place limits on models containing relativistic species at the decoupling epoch. With Planck+WP+HighL+HST data we will analyse sterile neutrino as dark radiation with (3+1) and (3+2) scenario. We will review the most recent cosmological results including a complete investigation of the dark radiation sector in order to provide an overview of models that are still compatible with new cosmological observations. Furthermore, we will update the cosmological constraints on neutrino physics and dark radiation properties focusing on tensions between data sets and degeneracies among parameters that can degrade our information or mimic the existence of extra species. Leptogenesis properties due to extra sterile neutrinos will also be investigated.

Dark Radiation

Also we will study sterile neutrino as dark radiation. Recent cosmological data favour additional relativistic degrees of freedom beyond the three active neutrinos and photons, often referred to as 'dark' radiation. Light sterile neutrinos is one of the prime candidates for such additional radiation. However, constraints on sterile neutrinos based on the current cosmological data have been derived using simplified assumptions about thermalisation of the sterile neutrino at the Big Bang Nucleosynthesis (BBN) epoch. These assumptions are not necessarily justified and here we will solve the full quantum kinetic equations in the (3 active + 1(2) sterile) scenario and derive the number of thermalised species just before BBN begins initial lepton asymmetry and for a range of possible mass-mixing parameters. We will investigate about the partial and full thermalisation assumption during the BBN epoch for initial small/large lepton asymmetry.