

# Probing supernova physics with neutrino oscillations

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We point out that solar neutrino oscillations with large mixing angle as evidenced in current solar neutrino data have a strong impact on strategies for diagnosing collapse-driven supernova (SN) through neutrino observations. Such oscillations induce a significant deformation of the energy spectra of neutrinos, thereby allowing us to obtain otherwise inaccessible features of SN neutrino spectra. We demonstrate that one can determine temperatures and luminosities of non-electron flavor neutrinos by observing  $\bar{\nu}_e$  from galactic SN in massive water Cherenkov detectors by the charged current reactions on protons.

## I. INTRODUCTION

The historical observation of neutrinos from the supernova (SN) 1987A at the Kamiokande [1] and IMB [2] detectors had a great impact and confirmed the basic picture of stellar collapse and SN explosion [3]. However, the number of observed events was too small to draw definite conclusions about the explosion mechanism or detailed properties of SN neutrinos. Hopefully, the next SN in our galaxy will be detected by several massive neutrino detectors, currently operating or planned. Such observations of neutrinos from a galactic SN should provide us a far more detailed information on properties of SN neutrinos, as well as the newly formed neutron star, thus bringing substantial progress to our understanding of stellar collapse.

The discovery of atmospheric neutrino oscillations at Super-Kamiokande (SK) [4] implies that neutrinos have masses and different neutrino flavors mix, and it is supported by the results from the first long-baseline neutrino oscillation experiment, K2K [5]. Moreover, a clear evidence for solar neutrino oscillations into mu/tau neutrinos has been obtained by combining the Sudbury Neutrino Observatory (SNO) charged current (CC) measurement [6] with elastic scattering measurement at SK [7] and the most recent *in situ* CC and neutral current (NC) measurements at SNO [8].

Neutrino oscillations add a new “complication” to the diagnostics of SN neutrinos, since it is no longer true that a neutrino  $\nu_\alpha$  leaving the neutrinosphere with definite flavor  $\alpha$  will be detected on Earth as the same neutrino species. Then, the task of extracting information such as the original of neutrino spectra in the SN core from terrestrial observations, requires solving an “inverse problem”.

In this letter, we point out that rather than a “complication” the neutrino oscillation provides a new powerful tool for probing otherwise inaccessible features of SN neutrino spectra. This holds if the mixing angle responsible for the solar neutrino oscillation is large [9] as clearly indicated by the current solar neutrino data.

We show that a high statistics observation of  $\bar{\nu}_e$  through the CC reaction  $\bar{\nu}_e + p \rightarrow n + e^+$  will enable us to extract not only the original temperature of  $\bar{\nu}_e$  but also that of  $\bar{\nu}_{\mu(\tau)}$  at the neutrinosphere, as well as their time integrated luminosities. In order to determine these parameters we employ a  $\chi^2$  method to “separate” two different neutrino spectra at the neutrinosphere with different temperatures and luminosities. Hereafter we use a collective notation  $\nu_x$  ( $\bar{\nu}_x$ ) for  $\nu_{\mu(\tau)}$  ( $\bar{\nu}_{\mu(\tau)}$ ) because they cannot be distinguished by their physical properties inside the SN.

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We focus on  $\bar{\nu}_e$  observation for the following reasons: (i) this is expected to be the channel with highest statistics in a large water Cerenkov detectors such as SK, Hyper-Kamiokande (HK) or UNO detectors, which are under consideration [10]. Neutrinos from a galactic SN at 10 kpc would produce 7000-10000 events at SK and  $2\text{-}3 \times 10^5$  events at HK [11]. (ii) the large solar neutrino mixing angle necessarily implies that the  $\bar{\nu}_e$  spectrum observed at the Earth is a strong mixture of two originally different SN neutrino spectra of  $\bar{\nu}_e$  and  $\bar{\nu}_x$ . This fact has been used to derive various constraints on neutrino mixing parameters [12–14]. Complementary information may be obtained also through direct detection of  $\bar{\nu}_x$  through the NC reaction either at SNO or KamLAND [15].

In addition to generic features of SN neutrino spectra obtained in SN simulations [3,16–19] we will take into account some new features indicated by recent studies. Most importantly, they include a new parameter which characterize the departure from the equipartition of integrated luminosities to electron and other flavor neutrinos, the quantity of greatest uncertainty in SN simulations. (See below.)

## II. SUPERNOVA NEUTRINOS; BASIC PROPERTIES

We now briefly summarize the features of neutrino spectra relevant for our work. In a SN explosion driven by gravitational collapse, about 99 % of the total binding energy of the neutron star,  $E_b \simeq 3 \times 10^{53}$  erg, is released in the form of neutrinos during the first  $\sim 10$  seconds after the onset of core collapse. It is well known that the time-dependent energy spectrum of each neutrino species can be approximated by a “pinched” Fermi-Dirac (FD) distribution [18]. In this work, we assume that the time-integrated spectra can also be well approximated by the pinched FD distributions with an effective degeneracy parameter  $\eta$

$$f(E) \propto \frac{E^2}{e^{E/T-\eta} + 1}, \quad (1)$$

where  $E$  denotes the neutrino energy, and  $T$  the effective temperature. We have checked the validity of this approximation by using results of  $20 M_\odot$  simulation by Mayle and Wilson [16,20]; we take in our analysis  $\eta = 2.6$  and  $\eta = 0$  for  $\bar{\nu}_e$  and  $\bar{\nu}_x$ , respectively, which reproduce well the time-integrated spectra.

Because of the hierarchy in strength of interactions with the surrounding matter neutrino temperatures obey  $\langle T_{\nu_e} \rangle < \langle T_{\bar{\nu}_e} \rangle < \langle T_{\nu_x} \rangle \simeq \langle T_{\bar{\nu}_x} \rangle$  as confirmed by various SN simulations. Typical values of the average energies of the time-integrated neutrino spectra obtained are  $\langle E_{\nu_e} \rangle \sim 12$  MeV,  $\langle E_{\bar{\nu}_e} \rangle \sim 15$  MeV and  $\langle E_{\nu_x} \rangle \simeq \langle E_{\bar{\nu}_x} \rangle \sim 24$  MeV. We introduce, for later use, a new parameter  $\tau_E$  which is defined as the ratio of the average energies of the time-integrated neutrino spectra,

$$\tau_E \equiv \frac{\langle E_{\bar{\nu}_\mu} \rangle}{\langle E_{\bar{\nu}_e} \rangle}. \quad (2)$$

SN simulations indicate  $\tau_E \sim 1.25 - 2.0$ .

Recent studies and SN simulations indicate various new features which were not taken into account in previous studies. There are three effects at least. The first is the possibility of a gross violation of equality in integrated luminosities of  $\nu_e/\bar{\nu}_e$  and  $\nu_x/\bar{\nu}_x$  by up to  $\sim 50$  % [21]. The second is a violation of equality of physical properties of  $\nu_x$  to  $\bar{\nu}_x$  due to the effects of weak magnetism [22]. The third is possible difference in integrated luminosity between  $\bar{\nu}_e$  and  $\nu_e$  [21,23,24].

The actual situation regarding violation of equipartition can be less dramatic since the  $\nu_e\bar{\nu}_e$  annihilation process enhances the  $\nu_x/\bar{\nu}_x$  luminosity, as recently shown by Buras *et al.* [23]. However, we prefer to introduce a free fit parameter  $\xi$  defined as a ratio of integrated luminosities of  $\bar{\nu}_x$  to  $\bar{\nu}_e$ ;

$$\xi \equiv \frac{E_{\bar{\nu}_x}^{tot}}{E_{\bar{\nu}_e}^{tot}}, \quad (3)$$

where  $E_{\bar{\nu}_\alpha}^{tot} \equiv \int L_{\bar{\nu}_\alpha} dt$  and  $\xi = 1$  in the equipartition limit. It quantifies the departure from equipartition of integrated luminosities to  $\bar{\nu}_e$  and  $\bar{\nu}_x$ . On the other hand, we ignore the latter two effects in this paper. We feel that taking into account the uncertainty in  $\xi$  gives us a reasonable framework at least as a first approximation; the other effects are not very sizable,  $\lesssim 10$  %, and may cancel with each other, e.g., effects of [22] and [23] on temperatures of  $\nu_x$  to  $\bar{\nu}_x$ . Therefore, we treat  $E_{\bar{\nu}_e}^{tot}$ ,  $T_{\bar{\nu}_e}$ ,  $E_{\nu_x}^{tot} = E_{\bar{\nu}_x}^{tot}$ , and  $T_{\nu_x} = T_{\bar{\nu}_x}$  as free fit parameters.

### III. ANALYSIS METHOD

Taking the best-fit values of mixing parameters from the latest analysis of the solar neutrino data [25], we compute the conversion probability for  $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$  oscillations in the SN envelope, following the prescription in Ref. [26], assuming an approximate power-law density profile,  $\rho(r) \sim r^{-3}$ . For simplicity, we neglect possible Earth matter effects [27] which will depend on the location of the detectors. In the context of three-neutrino flavor mixing, our treatment applies to the normal mass ordering ( $\Delta m_{atm}^2 > 0$ ) and the inverted mass ordering ( $\Delta m_{atm}^2 < 0$ ) with non-adiabatic high-density resonance [13,28], where  $\Delta m_{atm}^2$  denotes the atmospheric neutrino mass squared difference. Further implications of our proposal for the case of generic three flavor mixing will be given in Ref. [29].

We take, for definiteness, the SK and the HK detectors and assume their fiducial volumes as 32 kton and 1 Mton, respectively. We assume  $\bar{\nu}_e$ 's will come from a galactic SN located at 10 kpc from the Earth. We only consider  $\bar{\nu}_e$  CC reaction on proton and neglect contribution from  $\nu_\alpha e$  elastic scattering and CC reactions on oxygen in our analysis. It should give a good approximation because these processes have very small cross sections. The effect of weak magnetism is taken into account [30]. Without knowing the detection efficiency and energy resolution expected at HK, we assume that they are the same as those in SK and set the threshold energy to 5 MeV [29].

Lacking real galactic SN neutrino data at hand, we generate an artificial data set by adopting the model spectra as described before. We first define arbitrarily a set of initial values for the four relevant astrophysical SN parameters  $\alpha^0 \equiv \{E_b^0, \langle E_{\bar{\nu}_e} \rangle^0, \tau_E^0, \xi^0\}$  as ‘‘true values’’ given by nature. The data thus generated,  $N_i^{\text{obs}} \equiv N_i(\alpha^0)$ , are taken as the ‘‘observed’’ values. To quantify how well a single FD distribution can be discriminated from a superposition of two FD distributions we employ a  $\chi^2$  minimization fit in the space of four astrophysical parameters  $\alpha \equiv \{E_b, \langle E_{\bar{\nu}_e} \rangle, \tau_E, \xi\}$ . The  $\chi^2$  function is defined as

$$\chi^2 \equiv 2 \times \sum_{i=1}^{N_{bin}} \{N_i(\alpha) - N_i(\alpha^0) + N_i(\alpha^0) \ln[N_i(\alpha^0)/N_i(\alpha)]\}, \quad (4)$$

where  $N_{bin} = 20$ . For simplicity, we present below the results obtained when event-by-event fluctuations of the artificial data set are neglected. However, we have explicitly verified that our results agree well with the ones obtained by generating 10,000 sets of Gaussian fluctuated data.

Current solar neutrino data strongly favor the large mixing angle (LMA) MSW solution. Therefore, we focus on the LMA solution. It also gives a conservative estimate of the oscillation effect compared to the LOW and the VAC solutions because the effect is larger for larger mixing angles.

### IV. RESULTS AND DISCUSSIONS

We show in Fig. 1 the  $3\sigma$  C.L. allowed parameter region obtained in the  $\langle E_{\bar{\nu}_e} \rangle - \tau_E$  and  $\langle E_{\bar{\nu}_e} \rangle - E_b$  planes for SK and HK detectors by assuming the LMA solution, taking the best-fit value for mixing angle,  $\tan^2 \theta = 0.42$  [25]. We also present results for the no-oscillation case for comparison. We set the initial astrophysical parameters as  $\langle E_{\bar{\nu}_e} \rangle^0 = 15$  MeV,  $\tau_E^0 = 1.4$ ,  $E_b^0 = 3 \times 10^{53}$  erg, and  $\xi^0 = 0.5$ .

Fig. 1 demonstrates that we can extract the both  $\bar{\nu}_e$  and  $\bar{\nu}_x$  temperatures in the presence of large mixing oscillations. The accuracies we can achieve with the LMA best-fit parameters are  $\Delta\tau_E/\tau_E \sim 9$  (1.5) %,  $\Delta\langle E_{\bar{\nu}_e} \rangle/\langle E_{\bar{\nu}_e} \rangle \sim 4$  (1) In contrast, in the absence of oscillation there is no sensitivity in  $E_b$  due to the inability of determining  $\nu_x$  and  $\bar{\nu}_x$  luminosities. The improvement in the accuracy of the determination of these quantities for the oscillation case is remarkable, especially with HK.

Let us now examine how accurately we can determine the equipartition-violation parameter  $\xi$  and its correlation with  $\tau_E$  and  $E_b$ . This is shown in Fig. 2. We note that the accuracy of  $\tau_E$  determination is remarkably good in spite of the rather poor accuracy in the knowledge of  $\xi$ . It should be noticed that Fig. 2 demonstrates that HK can do a much better job for  $\xi$ ,  $\Delta\xi/\xi \sim 10$  %. We emphasize that without having sensitivity to  $\xi$  we can not determine  $E_b$  in a good accuracy, as they are strongly correlated (See the right panel of Fig. 2.) We finally note that HK's enormous sensitivity  $\sim 10$  % may mean one could potentially examine the problem by treating accreting and thermal phase separately under the present approximations.

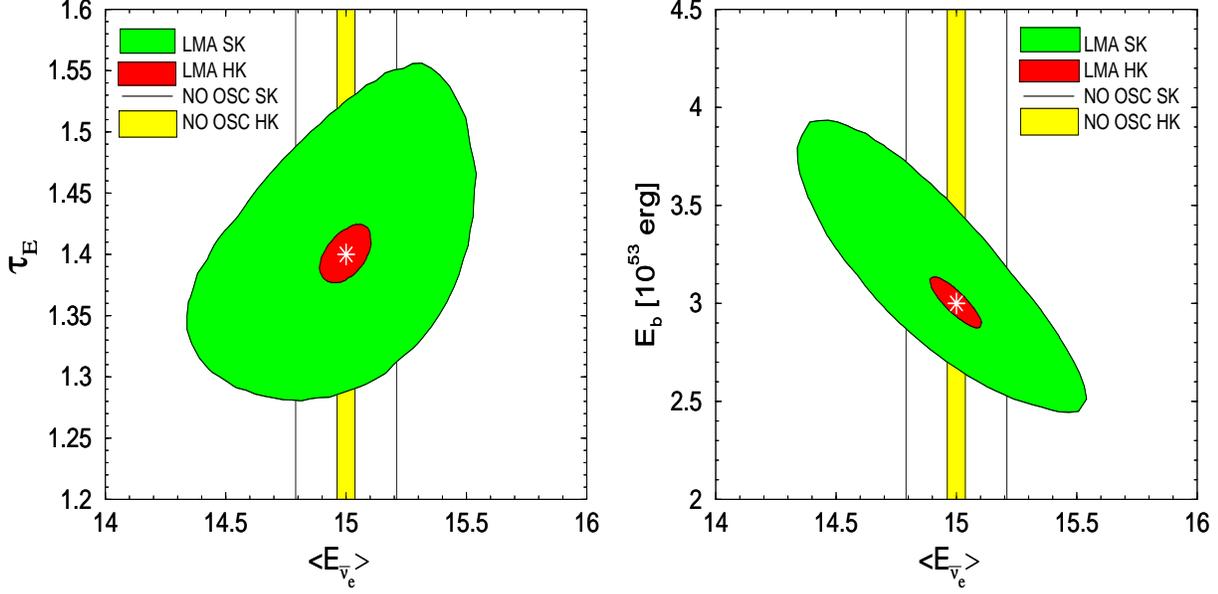


FIG. 1. Extracting the astrophysical parameters. The figure shows  $3\sigma$  contours assuming  $\langle E_{\bar{\nu}_e} \rangle^0 = 15$  MeV,  $\tau_E^0 = 1.4$ ,  $E_b^0 = 3 \times 10^{53}$  erg, and  $\xi^0 = 0.5$  for the SK and HK detectors assuming the LMA solution to the solar neutrino problem. Best fits are indicated by the stars.

The negative correlation between  $\xi$  and  $\tau_E$  can be understood due to the fact that the effect of lowering  $\xi$ , which implies a decrease of the relative contribution of  $\bar{\nu}_x$ , can be compensated by increasing  $\tau_E$  to keep the higher energy tail of the observed spectrum similar. On the other hand, the strong positive correlation between  $\xi$  and  $E_b$  just reflects the relationship  $E_b = 2(1 + 2\xi)E_{\bar{\nu}_e}^{tot}$ , which is valid under our approximation  $E_{\nu_e}^{tot} = E_{\bar{\nu}_e}^{tot}$ . The correlation is robust and exists with and without oscillations as indicated in Fig. 2.

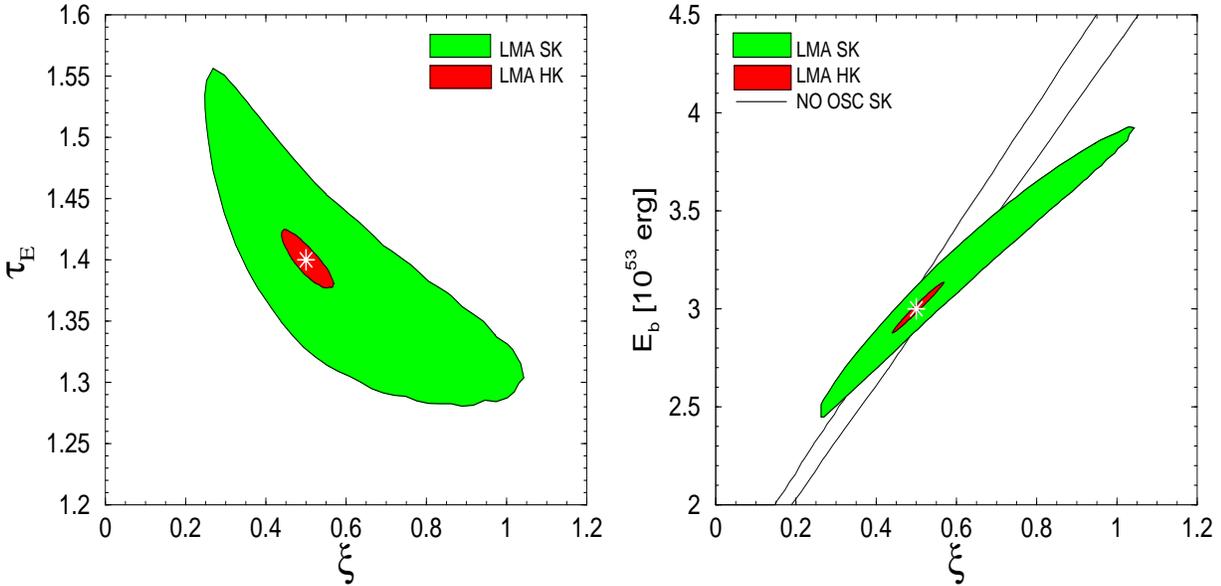


FIG. 2. Determination of the non-equipartition parameter  $\xi$  and its correlations with  $\tau_E$  and  $E_b$ . Same assumptions as in Fig. 1.

We have also examined the case of a smaller value of the initial  $\bar{\nu}_x$  energy,  $\tau_E^0 = 1.25$  to verify the robustness of our results. We found that although the sensitivity to  $E_b$  determination worsens by a factor of  $\sim 2$ , we still have a reasonable sensitivity to  $\tau_E$ ,  $\Delta\tau_E/\tau_E \sim 14\%$  (2.5% for HK), excluding the case of  $\tau_E = 1$  at  $3\sigma$ . See Ref. [29] for details.

We have verified that our results do not change very much even if we relax our assumptions by taking into account deviations from power-law density profile of progenitor star, or from the precise best-fit values of solar neutrino mixing parameters we have adopted. The inclusion of possible Earth matter effects for a given experiment will imply some regeneration effect. Although this will somewhat weaken our results, the effect is rather small in practice. Additional details related to the robustness of our method can be found in Ref. [29].

In summary, we have suggested a simple but powerful way of extracting separately the temperatures of both  $\bar{\nu}_e$  and  $\bar{\nu}_{\mu(\tau)}$  as well as their integrated luminosities by analyzing  $\bar{\nu}_e$  events that would be recorded by massive water Cherenkov detectors in the event of a galactic supernova explosion. In particular, an extraordinary power of megaton-class detectors (Hyper-Kamiokande or UNO) are noticed with regard to the determination of the integrated luminosities of  $\bar{\nu}_e$  and  $\bar{\nu}_{\mu(\tau)}$  as independent fit parameters. We stress that the large mixing between  $\nu_e$  and  $\nu_{\mu(\tau)}$ , which is clearly indicated by the current solar neutrino data, is essential in determining temperature as well as luminosity of  $\bar{\nu}_{\mu(\tau)}$ , and this must have more profound implications which await further investigation.

Note added:

When the first version of this paper was ready for submission to the electronic archive we became aware of the paper by Barger *et al.* [31] who pursued the similar strategy as ours. However, they do not treat the violation of equipartition of energies as a fit parameter.

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