The Supernova Relic Neutrino Background

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An upper bound to the supernova relic neutrino background from all past Type II supernovae is obtained using observations of the Universal metal enrichment history. We show that an unambiguous detection of these relic neutrinos by the Super-Kamiokande detector is unlikely. We also analyze the event rate in the Sudbury Neutrino Observatory (where coincident neutrons from $\bar{\nu}_e D \to n e^+$ might enhance background rejection), and arrive at the same conclusion. If the relic neutrino flux should be observed to exceed our upper bound and if the observations of the metal enrichment history (for $z < 1$) are not in considerable error, then either the Type II supernova rate does not track the metal enrichment history or some mechanism may be responsible for transforming $\bar{\nu}_{\mu,\tau} \to \bar{\nu}_e$.

I. INTRODUCTION

A Type II supernova (SN II) – the explosion triggered by the gravitational collapse of a single massive star – emits 99% of its energy in neutrinos. The relic $\bar{\nu}_e$ background created by all past SN II is potentially detectable in present and/or future large underground neutrino detectors. One of the goals of the current SuperK and SNO detectors is to detect this SRN background $^{1,2}$. The predicted SN II relic $\bar{\nu}_e$ (SRN) flux depends crucially on the SN II rate as a function of redshift and the epoch of maximum SN rate (throughout the SN rate refers to the comoving densities of the SN II rate) is important in determining the detectability of the SRN background. For example, if the SN rate should peak at redshifts of order 2 to 3, the majority of the SRNs would be redshifted to energies below typical detector threshold energies ($\sim 5$ MeV). Since the same objects which are responsible for creating the SRN background are also responsible for the bulk of the heavy element production, knowledge of the SN II metal and neutrino production, in concert with the observationally inferred metal enrichment history of the Universe, is the straightest path (i.e., least model dependent) to predicting the flux and spectrum of relic $\bar{\nu}_e$ from all past SN II $^{1}$. It is our goal here to follow this path in providing a generous upper bound to the expected SRN background. Furthermore, we account for the characteristics of the SuperK and SNO detectors, and use our calculated (upper bound to the) SRN background to predict (upper bounds to) the event rates at these detectors. These event rates are compared to expected backgrounds and to current limits. The current upper limit $^{3}$ (from the Kamiokande II detector) on the flux of supernova relic $\bar{\nu}_e$ in the energy interval from 19 to 35 MeV is $226 \text{ cm}^{-2}\text{sec}^{-1}$. SNO is just beginning operation and has not decided upon a neutron detection strategy which is vital to the detection of $\bar{\nu}_e$.

In the last few years progress has been made in constraining the recent star formation history of the Universe. In particular, a variety of observational evidence seem consistent with a comoving star formation rate (SFR) density which was much higher at redshifts $z \sim 1$ than at the present epoch. The history of star formation beyond $z \sim 1$ is less certain and it is not yet clear if the Universal SFR declined rapidly or evolved only mildly at higher redshifts. Support for this scenario comes from Pei & Fall $^{5}$ who have used chemical evolution models to explore the SFR and metal enrichment history inferred from observations of damped Ly$\alpha$ systems. They find that the observed H I column densities may not represent the true column densities because of significant corrections due to dust. Since the Ly$\alpha$ systems are identified from the spectra of quasars and since the Ly$\alpha$ systems may contain dust, the implication is that some of the quasars may be invisible. This, in turn, suggests that some Ly$\alpha$ systems may go undetected. When Pei & Fall correct for the effects of dust obscuration, they find evidence for rapid star formation at low redshifts ($z \sim 1$). This is to be compared to the predicted peak star formation rate epoch at redshifts of order $3 - 4$ when obscuration is not taken into account. In particular, for their model with infall Pei & Fall find that the observational data is consistent with a SFR which increases until $z \sim 1$ and then decreases with further increases in redshift. Independent observations by Madau $et$ $al.$ $^{5}$ of the metallicity enrichment rate (MER) are in excellent agreement with the Pei & Fall results. The direct quantitative support for Pei & Fall’s model comes from the Canada-France redshift survey of faint galaxies $^{11}$ which found that the comoving UV luminosity density of the Universe shows a sharp decline from $z \sim 1$ to the present.

$^{1}$Type I supernovae are not expected to contribute appreciably to the relic neutrino background.
Here, using the model of Pei and Fall, we parameterize the metal enrichment history (MER) observed by Madau et al. [13] to predict the SN II relic $\bar{\nu}_e$ flux at Earth. In the past, similar calculations of this relic $\bar{\nu}_e$ flux have been done by Totani & Sato [24], Totani, Sato & Yoshii [25], Malaney [29] and Hartmann & Woosley [30]. In contrast to almost all of the above analyses, we strive to minimize any model dependences by directly relating the supernova rate and its evolution to observations of the metal enrichment history to obtain supernova rate and, thereby, the SRN flux. In our calculations we make always make “conservative” choices of any uncertain parameters so as to obtain a robust upper bound to the SRN flux. From this upper bound we will conclude that it is unlikely SuperK will detect these relic neutrinos (because the signal will be buried under a large background event rate) and that the event rate in SNO should be vanishingly small. In §II, we outline the formalism for calculating the flux of SRN at Earth. In §III, we calculate conservative (i.e., generous) upper bounds to the relic $\bar{\nu}_e$ event rates at SuperK and SNO. In §IV, we review previous estimates of the SRN flux in comparison with ours and we examine neutrino oscillations as a possible mechanism for increasing the SN relic $\bar{\nu}_e$ flux.

II. THE SUPERNOVAE RELIC NEUTRINO SPECTRUM

The spectrum of neutrinos at Earth due to all past supernovae depends on the differential (per unit energy interval) neutrino flux from each SN, on the redshift distribution of the SN rate, and on an assumed Friedmann-Robertson-Walker cosmology which may be parameterized by the Hubble parameter $H_0$ and the matter density parameter $\Omega_0$. For simplicity we ignore any possible cosmological constant at this point and discuss its effect later. If the supernova rate per unit comoving volume at redshift $z$ is $N_{\text{SN}}(z)$ and the neutrino energy distribution at the source (at energy $\epsilon$) is $\mathcal{L}_\nu^{\text{SN}}(\epsilon)$, then the differential flux of relic neutrinos at Earth is given by

$$j_\nu(\epsilon) = \frac{c}{H_0} \int_0^\infty \frac{d\epsilon}{1 + z} \frac{N_{\text{SN}}(z) \langle \mathcal{L}_\nu^{\text{SN}}(\epsilon') \rangle}{(1+z)\sqrt{1+\Omega_0 z}},$$

where $\epsilon' = (1+z)\epsilon$ and the neutrinos are assumed to be massless. The angled brackets indicate that the dependence of the neutrino flux on supernova progenitors with different masses should be averaged over the initial mass function (IMF). In practice we will choose values for these average quantities so as to maximize the SRN background.

The spectrum of the neutrinos from a supernova is parameterized as a Fermi-Dirac distribution with zero chemical potential, normalized to the total energy in a particular neutrino species ($E_\nu$) emitted by the supernova, i.e., $\int \mathcal{L}_\nu^{\text{SN}}(\epsilon) d\epsilon = E_\nu$. Then, for each neutrino species $\nu$,

$$\mathcal{L}_\nu^{\text{SN}}(\epsilon) = E_\nu \times \frac{120}{7\pi^4} \times \frac{\epsilon^2}{T_\nu^2} \times \left[ \exp\left( \frac{\epsilon}{T_\nu} \right) + 1 \right]^{-1}.$$

(2)

The neutrino luminosity is thus characterized by $E_\nu$ and $T_\nu$ which, in turn, depend on the SN progenitor mass. However, the problem of obtaining the IMF-averaged neutrino flux simplifies because $T_\nu$ does not vary rapidly as the SN progenitor mass is changed [7]. Adopting a flat $\Omega_0 = 1$ cosmology, and setting $x = 1 + z$, we can then write eq. (2) to a good approximation as

$$j_\nu(\epsilon) = A \frac{\langle E_\nu \rangle}{\langle T_\nu \rangle} \epsilon^2 \int_1^\infty dx \frac{\sqrt{x}}{\exp(\epsilon x / \langle T_\nu \rangle) + 1},$$

(3)

where $A = (120/7\pi^4) c H_0^{-1} = 1056 h_{50}^{-1}$ Mpc, with $H_0 = 50 h_{50}$ km/s/Mpc. The results of Woosley et al. [3] for a 25 $M_{\odot}$ supernova progenitor are used to fix $\langle E_\nu \rangle = 11 \times 10^{52}$ ergs and $\langle T_\nu \rangle = 5.3$ MeV. The values of $\langle E_\nu \rangle$ and $\langle T_\nu \rangle$ characterize the detectable $\bar{\nu}_e$ supernova neutrino spectrum. For comparison, recall that the data from SN 1987A gave $E_\nu = 8 \times 10^{52}$ ergs and $T_\nu = 4.8$ MeV [3]. Another issue concerns the role of the IMF and selection of the $\langle E_\nu \rangle$ and $\langle T_\nu \rangle$ values as averages. To obtain an upper bound to the detection rate, we use values of $\langle E_\nu \rangle$ and $\langle T_\nu \rangle$ which provide upper bounds to any reasonable average. This is possible because the flux integrated over the observable energy window (and hence the event rate) is an increasing function of both $\langle E_\nu \rangle$ and $\langle T_\nu \rangle$. The value of $T_\nu$ is particularly insensitive to the progenitor mass because $T_\nu$ derives its value from the temperature of the neutrinosphere formed during the collapse and the thermodynamic properties of the neutrinosphere (as long as it is well-defined) do not vary much with mass [3]. In particular, $T_\nu \sim 4 - 5$ MeV with 5.3 MeV being at the the upper end of the range. Thus, guided by models and SN 1987A, we parameterize the neutrino flux from supernovae so as to obtain a conservative upper bound to the SRN event rate.

Under the assumption that the supernova rate tracks the metal enrichment rate, the supernova rate used to calculate the relic neutrino flux can be written as
\[ N_{\text{SN}}(z) = \langle \rho_{Z}(z) \rangle_{M_{Z}} \]  

where \( \langle M_{Z} \rangle \) is the average yield of "metals" \((Z \geq 6)\) per supernova and \( \rho_{Z} \) is the metal enrichment rate per unit comoving volume. We have implicitly assumed that the metals come from SN II, consistent with nucleosynthesis arguments [3] which show that the metal enrichment role of SN Ia is secondary to that of SN II. In any case, by neglecting SN Ia we overestimate the SRN flux (albeit, by only a factor of 2 at most). The other point to be noted here concerns our use of the metal enrichment history instead of the possibly more direct SFR to compute the SN rate. Both the SFR and the metal enrichment rate can be inferred from observations of the UV luminosity of star forming galaxies. But unlike the SFR which has a steep dependence on the adopted IMF, the metal enrichment rate is less sensitive to the IMF because the same (heavier) stars which are more UV luminous also eject more metals [4]. Thus, the SN rate is more closely tied to the metal enrichment history than to the SFR.

To parameterize the evolution of \( \rho_{Z}(z) \) from the present back to \( z = 1 \), we use the results of Pei & Fall. In particular, we use the comoving metal production rate for their case with infall (Fig.1 of [7]) which is in good quantitative agreement with SFR observations at \( z < 1 \) [11, 14]. Since the neutrino flux from individual supernovae falls rapidly with increasing energy, and the lower energy neutrinos from high redshift supernovae are redshifted below the threshold of detectability, our predictions are relatively insensitive to the high redshift \((z > 1)\) behavior (as also noted by Hartmann & Woosley [30]). This is fortunate since it is difficult to quantify precisely the \( z > 1 \) evolution. For these reasons, we make the simplifying conservative assumption that the supernovae rate remains constant at higher redshifts: \( N_{\text{SN}}(z > 1) = N_{\text{SN}}(z = 1) \). It should be noted that the \( z < 1 \) evolution adopted here is likely quite robust in that independent studies reveal the same pattern of evolution (including, for example, that of the QSO luminosity density [11] and the different observational data are in good quantitative agreement. Nevertheless, some changes to our adopted chemical enrichment history could be envisaged based on the arguments that the role of dust at high redshifts is still uncertain and, perhaps not all the star formation at higher redshifts has been observed [10, 13, 14]. However, the relative insensitivity of our upper bound to the high redshift behavior insulates it against such uncertainty.

To determine the average amount of metals ejected per supernova, the results of calculations of supernova nucleosynthesis by Woosley and Weaver [3] are employed. From their published tables of the elemental composition of the ejecta, it can be ascertained that the heavy element yield ranges from \( M_{Z} = 1.1 \, M_{\odot} \) for a 15 \( M_{\odot} \) SN progenitor to \( M_{Z} = 4.2 \, M_{\odot} \) for 25 \( M_{\odot} \). These results are for an initial metallicity equal to 0.1 \( Z_{\odot} \), which we assume characterizes the metallicity at redshifts around unity. In any case, the \( M_{Z} \) values for SN progenitors with initial metallicity equal to \( Z_{\odot} \) is greater by about 10-20\% which, if used, would lead to a decrease in the predicted flux. Keeping in mind that the rate of events varies inversely as \( \langle M_{Z} \rangle \), we set \( \langle M_{Z} \rangle \) equal to 1 \( M_{\odot} \) in the interest of obtaining an unambiguous upper bound. In Figure 1 we show the SRN spectrum that results from our adopted metal enrichment history and a conservative lower bound to the SN metallicity yields, \( \langle M_{Z} \rangle = 1 \, M_{\odot} \).

III. EVENT RATE AT SUPERK AND SNO

It is not possible to detect SN relic neutrinos at all energies. For SuperK the observable energy window is likely to be from 19 to 35 MeV. Below 10 MeV, the \( \bar{\nu}_{e} \) from reactors [2] and the Earth will completely overwhelm the relic neutrinos. Above 10 MeV and below the observable energy window, the main source of background is due to the solar neutrinos, radiation from outside the fiducial volume and spallation-produced events due to the cosmic-ray muons in the detector [3]. Above 19 MeV the background is primarily due to atmospheric neutrinos [2]. At energies greater than about 35 MeV, the rapidly (exponentially) falling SRN flux (peaked around 3 MeV) becomes smaller than the atmospheric \( \bar{\nu}_{e} \) flux, as can be verified from Figure 1. Therefore the observable flux is obtained by integrating the differential flux over the neutrino energy range from 20.3 to 36.3 MeV (since \( \epsilon = E_{\nu} + 1.3 \) MeV where \( E_{\nu} \) is the energy of the positron and 1.3 MeV is the neutron – proton mass difference). We will also quote results in the more optimistic energy window of 15 – 35 MeV in the hope that with better background subtraction, SuperK will be able to probe these lower energy relic neutrinos. Detection of the SRN background in the much smaller SNO detector may be possible using coincident neutrons from \( \bar{\nu}_{e}p \rightarrow ne^{+} \). Because neutron detection at SNO is still in its infancy, we quote the total SNO event rate for positron energies above 10 MeV, corresponding to our SRN background.

To calculate the event rate at SuperK, the detector is assumed to be 100\% efficient in the observable energy window. The dominant reaction is \( \bar{\nu}_{e}p \rightarrow ne^{+} \) with a cross section \( (\sigma_{p}(\epsilon)) \) two orders of magnitude larger than that of the scattering reaction \( (\nu_{e}e \rightarrow \nu_{e}e) \). The differential event rate in the interval \( d\epsilon \) is then \( N_{p}\sigma_{p}(\epsilon)\langle j_{p}(\epsilon) \rangle d\epsilon \) and the predicted event rate at the detector is:

\[
R = AN_{p} \frac{\langle E_{\nu} \rangle}{(T_{\nu})^{4}} \int_{1}^{\infty} dx \, N_{\text{SR}}(x) \sqrt{x} \int_{\epsilon_{1}}^{\epsilon_{2}} d\epsilon \, \frac{\epsilon^{2} \sigma_{p}(\epsilon)}{\exp(\epsilon/ \langle T_{\nu} \rangle) + 1} ,
\]  

3
where the \( \epsilon_i \) delineate the energy window (for this case, 20.3 and 36.3, respectively) and \( N_p \) is the number of free protons in the detector. For SuperK, with a fiducial volume of 22.5 ktons, \( N_p = 1.51 \times 10^{33} \).

Using the metal enrichment history to establish the supernova rate, the SN relic \( \bar{\nu}_e \) event rate at SuperK can be written as

\[
R = 0.066 \left( \frac{M_\odot}{\text{M}_Z} \right) \left( \frac{<E_\nu>}{10^{52} \text{ ergs}} \right) \left( \frac{T_\nu}{\text{MeV}} \right) \frac{\text{events}}{22.5 \text{ kton-year}}
\]

where we use \( \sigma_{\nu}(\epsilon) = 9.52 \times 10^{-44} E_\nu \rho_\nu \text{ cm}^2 \) with \( E_\nu \) and \( \rho_\nu \) (the energy and momentum of the positron) measured in MeV. We have set \( h_{50} = 1 \) in the interest of obtaining an upper bound to the event rate. Also, for the same reason the average metal yield per supernova is taken to be \( 1 M_\odot \), a lower bound to that obtained in the Woosley & Weaver models. For completeness we show in Figure 3 the differential rate of \( \bar{\nu}_e p \rightarrow ne^+ \) for our SRN background, with \( <E_\nu> = 11 \times 10^{52} \text{ ergs} \) and \( T_\nu = 5.3 \text{ MeV} \).

With our adopted SN parameters, the SRN event rate for a 22.5 kton-year exposure at SuperK is predicted to be

\[
\begin{align*}
R < 4 \text{ events} & \quad 19 \leq E_\nu(\text{MeV}) \leq 35, \\
R < 7 \text{ events} & \quad 15 \leq E_\nu(\text{MeV}) \leq 35.
\end{align*}
\]

Because the SRN spectrum falls rapidly with energy, the energy distribution of the events is strongly peaked at about 10 MeV (see Fig. 1; in 5 MeV bins from 10 MeV to 40 MeV, the percentages are 37:29:17:10:5:2). If the threshold could be lowered to 10 MeV, our upper bound to the event rate at SuperK would increase to about 10/year. In terms of the flux at the detector, the results are as follows: the upper bound to the SRN flux integrated over all energies is 54 \( \text{cm}^{-2} \text{sec}^{-1} \) while in the relevant energy window from 19 to 35 MeV, the flux is 1.6 \( \text{cm}^{-2} \text{sec}^{-1} \) (to be compared to the current upper bound of 226 \( \text{cm}^{-2} \text{sec}^{-1} \)). In the larger energy window from 15 to 35 MeV, the observable flux is 3.7 \( \text{cm}^{-2} \text{sec}^{-1} \). The reason for the large difference between the total and observable flux is two-fold. One, the observable energy window only captures the falling tail-end of the SRN spectrum and two, the event rate at low energies is artificially enhanced due to the SN rate which was assumed to be constant at high redshifts.

In the energy window from 19 to 35 MeV, the expected background event rate from the atmospheric \( \bar{\nu}_e \) interacting with the protons (\( \bar{\nu}_e p \rightarrow ne^+ \)) in the detector can be calculated. Using the atmospheric neutrino flux from Gaisser et al. [22], the event rate for this background to the SRNs is only about 0.5/yr (for 22.5 ktons of water). However, there is another source of background which is dominant. The atmospheric muon neutrinos interacting with the nucleons (both free and bound) in the fiducial volume produce muons. If these muons are produced with energies below Cerenkov radiation threshold (kinetic energy less than 53 MeV), then they will not be detected, but their decay-produced electrons and positrons will. Consequently, the muon decay signal will mimic the \( \bar{\nu}_e p \rightarrow ne^+ \) process in SuperK. The event rate from these muon decays was estimated to be around unity for 0.58 kton-yr exposure of the Kamiokande II detector, forming the principal source of background after the various cuts had been implemented [23]. Extrapolating to the fiducial volume of 22.5 ktons for SuperK, we expect that SuperK should see \(~39\) events/yr as background to the SRN events. Although our predicted signal is much smaller than the sub-Cerenkov muon background, it may still be detectable because the energy distributions of the signal and the background are distinctly different. In such a case, a conservative criterion for the detectability of the signal is that it be greater than the statistical fluctuations of the background. However, even with three years of data and assuming that the SRN flux is close to our upper bound, the SRN signal is only just about equal to the statistical fluctuations in the sub-Cerenkov muon background. This situation will improve, though not dramatically, if SuperK can lower its threshold (to SRN) to 15 MeV.

Lastly we mention the SNO detector. Although much smaller than SuperK, the 1 kton SNO hopes to detect the SRN background by using the unique 2 neutron final state in \( \bar{\nu}_e D \rightarrow nne^+ \). Using the cross section of Kubodera and Nozawa [23], the upper bound to the event rate above 10 MeV is a not-very-promising 0.1/yr/kton. Again we show the differential event rate in Figure 3. Note, however, that unlike the SRN signal in Super-K, this rate can be influenced by the large z SN rate, about which we know little.

**IV. DISCUSSION AND CONCLUSIONS**

**A. Previous works**

Supernova relic neutrinos have been the focus of many previous studies [1,3,7,24–30]. The fluxes predicted in these studies spread over some two orders of magnitude, primarily due to the uncertain determinations of the present number density of galaxies, the SN rate in our galaxy at present, and/or the SN redshift distribution. More recently,
Totani et al. [28] used the population synthesis method to model the evolution of star-forming galaxies and they obtained a prediction for the flux of SRN. They found an event rate at SuperK (in the energy interval from 15 to 40 MeV) of 1.2 yr\(^{-1}\) and the “most optimistic” prediction for their model was an event rate of 4.7/yr. Malaney [29] used the Pei & Fall results in order to parameterize the evolution of the cosmic gas density which he then uses to calculate the star formation rate and, from that, the past supernova rate, finding a total SRN flux, integrated over all energies, of 2.0 – 5.4 cm\(^{-2}\)sec\(^{-1}\) depending on somewhat arbitrary low redshift corrections to the supernova rate. The work of Hartmann & Woosley [30], using a SN rate proportional to \((1 + z)^{4}\) (motivated by [31]) and normalized to the SN rate at present as derived from the H\(\alpha\) observations of the local Universe is most similar to ours. Their “best” estimate of a relic neutrino flux is \(\sim 0.2\) cm\(^{-2}\)sec\(^{-1}\). Although they do utilize Pei & Fall beyond \(z \sim 1\), they (and we and others) have noted that this contribution is subdominant. However, Hartmann & Woosley [30] do not discuss the backgrounds to detecting the SRN and although their estimated flux is smaller than our upper bound by about a factor of five, they conclude the SRN may somehow be detectable. Although we agree with the Hartmann & Woosley estimate of the SRN flux in the sense that if we adopted their choices of parameters rather than our “conservative” choices we would predict the same flux, we disagree that this small flux is detectable.

All these previous results are similar to, while less than the upper bound obtained in this paper. In fact, if we use our analysis of the SN rate along with the same IMF as used by Totani et al. for their spiral galaxies (which harbor most of the Type II supernova [31,28]), our SRN event rate in the 15 to 40 MeV range (for comparison with Totani et al.) at SuperK falls to 1/yr. The total integrated flux falls to 11 cm\(^{-2}\)sec\(^{-1}\) while the result for the flux in the 15 to 40 MeV energy window becomes 0.5 cm\(^{-2}\)sec\(^{-1}\). These estimates agree well with those quoted from the previous works [28,30]. In fact, the value of 1 event/yr obtained using the IMF from Totani et al. amounts to choosing the variables \((M_\odot), \langle T_\nu \rangle\) and \(\langle E_\nu \rangle\) for an actual IMF rather than the extrema we have selected. It is more likely that any realistic IMF (chosen to fit other observables) when combined with a SN rate that peaks at \(z \sim 1\) (as implied by the metal enrichment history) will yield an event rate that is an order of magnitude smaller than the upper bound we quote. Our upper-bound is robust because it is derived directly from the metal enrichment history which suggests that the SN\(\nu\) rate can peak no earlier than \(z \sim 1\).

B. Choice of Cosmology

Throughout, we have assumed that \(\Omega_0 = 1\) and \(q_0 = 0.5\). It is of some interest to ask how our SRN background predictions change if we change the background cosmology. Reducing the non-relativistic matter density from critical \((\Omega_0 < 1)\), by allowing positive curvature and/or a cosmological constant \(\Lambda\), would reduce the expansion rate at late times and thereby increase the SRN flux, for the same \(H_0\). The event rate increases by about 40% in going from an \(\Omega_0 = 1\) to an \(\Omega_0 = 0.3, \Omega_\Lambda = 0.7\) Universe. But the estimation of the luminosity density (which is used to derive the metal enrichment rates) itself requires the assumption of a background cosmology and it typically increases less rapidly with redshift for cosmologies with smaller \(\Omega_0\) [31]. These two effects tend to cancel out leaving the expected event rate nearly unchanged. Thus we do not expect our results to change substantially for a different background cosmology.

C. Neutrino Oscillations

The main goal of our work has been to obtain the most optimistic estimate of the SRN event rate at SuperK with the intent that if results from SuperK should exceed this upper bound, it could provide hints of new physics beyond the standard model. Here, we consider neutrino oscillations as a mechanism for maximizing the SRN flux. Since \(\bar{\nu}_x\) (where \(x = \mu, \tau\)) only experience neutral current interactions, they decouple deeper in the SN where the temperature is higher. As a result, they stream out of the SN with a higher temperature than the \(\nu_e\). Because higher energy neutrinos are easier to detect, \(\bar{\nu}_e \leftrightarrow \bar{\nu}_x\) oscillations have the potential to increase the SRN event rate. The maximum effect for any scenario is attained when the mixing is maximal. We will assume a mass hierarchy wherein the electron neutrino is the lightest (however, for an inverted mass hierarchy and resonant conversion in the presence of magnetic fields, see [32]). This implies that the MSW resonance condition is not satisfied for \(\nu_e \leftrightarrow \bar{\nu}_x\), but vacuum oscillations can still occur. If all three flavors are maximally mixed, then the oscillation probabilities average out to 1/3 for any reasonable choice of mass differences because of the large distances traversed by the the relic neutrinos (typically of order of \(H_0^{-1}\); for the oscillation length to be comparable to this, \(\Delta m^2 \sim 10^{-25}\) eV\(^2\)). Such oscillations would make two-thirds of the original \(\bar{\nu}_x\) flux hotter as they would be “born” (would have oscillated from \(\bar{\nu}_x\)) with the same temperature as the \(\bar{\nu}_x\). To quantify the discussion here, we take \(\langle T_{\bar{\nu}_x} \rangle = 2\langle T_{\bar{\nu}_e} \rangle\) (we might be exaggerating the spectral difference between \(\bar{\nu}_x\) and \(\bar{\nu}_e\) considerably here [33]) and assume that the same amount of energy is expelled...
in all three flavors. This leads to an upper bound to the SRN event rate at SuperK of 11/yr with an observable flux of 4 cm$^{-2}$sec$^{-1}$ in the 19 – 35 MeV energy window. The upper bound is larger by about a factor of 3 as a result of the increase in the number of neutrinos in the exponential tail of the neutrino distribution (where the observable energy window lies), due to the increase in temperature. As before, $\langle M_Z \rangle$ has been set equal to 1 M$_\odot$. For the case where $\bar{\nu}_e$ is maximally mixed with only one of either $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$, the upper bounds are 9/yr and 3 cm$^{-2}$sec$^{-1}$ for the event rate and observable flux respectively. The upper bounds in the 15 – 35 MeV energy window are 14/yr for the three neutrino maximal mixing case, and 12/yr for the two neutrino maximal mixing case. In general, a decrease in the threshold (below 19 MeV) and neutrino oscillations seem to be required to boost the SRN flux to sufficient levels. Because the spectral shape of this oscillation enhanced SRN signal is sufficiently different from the sub-Cerenkov muon background, it may be detectable as a distortion of the expected muon background, if the SRN flux is in the vicinity of the upper bound we have quoted. For SNO, the two neutrino maximal mixing case gives an event rate of 0.25/yr/kton while the three neutrino maximal mixing increases the rate to 0.29/yr/kton.

A point to clarify here concerns the selection of the observable energy window given that the event rate in 19 – 35 MeV window is now relatively large. Due to the larger signal, the relic neutrinos only become sub-dominant to the atmospheric neutrinos around 60 MeV (for a relic neutrino flux close to the upper bound). In fact, integrating out to a neutrino energy of order 60 MeV would increase the SRN event rate by about 50%. However the background from muon decay would increase by more than a factor of 3. One possibility this opens up is to also use the energy window from about 55 to 70 MeV since the muon-decay background is cut off at $m_\mu/2$ (as decay occurs for muons at rest). For the same oscillation parameters as before, the upper bound to the event rate in the 55 to 70 MeV energy window is about 1/yr. However, the event rate due to the atmospheric neutrinos in the same energy window is of comparable magnitude and so, the situation is still not promising.

D. Conclusions

Using those observations most closely connected to the metal enrichment history of the Universe in order to relate the MER to the SNR, we have derived a robust upper bound to the supernova relic neutrino events at SuperK: 4 events in the energy window from 19 to 35 MeV for a 22.5 kton-yr exposure. We have argued that the SuperK signal is dominated by SN II from $z < 1$ and so it is insensitive to the high redshift behavior of the metal enrichment rate. We use only the generic features of gravitational collapse SN models which have been substantiated by observations of SN 1987A to characterize the $\bar{\nu}_e$ spectrum emergent from SN II. In combination, these facts argue for the robustness of the upper bound to the SRN event rate obtained here. In addition, we have analyzed the backgrounds to the SRN events and conclude it is unlikely that SuperK will be able to detect these SRN neutrinos, unless the Type II supernova rate does not track the metal enrichment rate, or the observations of the star formation rate which lead to estimates of the metal enrichment rate at $z < 1$ are in considerable error, and/or some physics beyond the standard model is at play. We also find that the event rate at SNO will most likely be too small to be detected. The effect of flavor oscillations on the SRN flux has also been studied and the maximum possible increase in the event rate is less than a factor of 3. If the original flux is close to the upper bound quoted here and the mixing close to maximal, SuperK just might see the SRN flux as a distortion in its sub-Cerenkov muon background.

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FIG. 1. The relevant event rates for the detection of supernova relic neutrinos (SRN), along with the predicted SRN spectral flux. The $\overline{\nu}_e p$ rate is for SRN detection at SuperK, while the $\overline{\nu}_e D$ rate applies for the SNO detector. The abscissa, energy, refers to the $\overline{\nu}_e$ energy for all the cases except for the $\mu$ decay rate where it corresponds to the decay-produced electron's energy ($E_e$) plus 1.3 MeV (i.e., what the energy of a $\overline{\nu}_e$ would have to be, in order to produce a positron with energy $E_e$ by $\overline{\nu}_e + p$ reaction.)