Reconstructing the supernova bounce time with neutrinos in IceCube

Francis Halzen$^1$ and Georg G. Raffelt$^2$

$^1$Department of Physics, University of Wisconsin, Madison, WI 53706, USA
$^2$Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

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Generic model predictions for the early neutrino signal of a core-collapse supernova (SN) imply that IceCube can reconstruct the bounce to within about ±3.5 ms at 95% CL (assumed SN distance 10 kpc), relevant for coincidence with gravitational-wave detectors. The timing uncertainty scales approximately with distance-squared. The offset between true and reconstructed bounce time of up to several ms depends on the neutrino flavor oscillation scenario. Our work extends the recent study of Pagliaroli et al. [Phys. Rev. Lett. 103, 031102 (2009)] and demonstrates IceCube’s superb timing capabilities for neutrinos from the next nearby SN.

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I. INTRODUCTION

The high-statistics neutrino observation from the next nearby supernova (SN) will provide a bonanza of information about the astrophysics of core-collapse phenomena and neutrino properties. In a recent Physical Review Letter a strong case was made for the importance of coincidence measurements between gravitational wave and neutrino signals from SN core bounce [1]. The largest existing SN neutrino detectors are Super-Kamiokande and IceCube, reaching to a distance of about 100 kpc. The expected distribution of galactic SNe drops off quickly beyond about 20 kpc [2]. At this “pessimistic” distance, Super-Kamiokande can time the bounce to within a few tens of milliseconds, an interval comparable to the expected duration of the gravitational wave burst [1].

We here extend this study to IceCube, a high-statistics SN neutrino detector that would have seen the SN 1987A neutrino signal with 5σ significance. For galactic SNe, the large rate of uncorrelated Cherenkov photons provides excellent time-structure information.

Following Ref. [1] we note that neutrino masses are small enough to neglect time-of-flight effects. Recalling that the diameter of the Earth is 42 ms, millisecond-coincidence measurements between detectors at different geographic locations requires determining the SN direction either by astronomical observations or by the electron-scattering signal in Super-Kamiokande.

II. SUPERNOVA NEUTRINOS IN ICECUBE

When SN neutrinos stream through water or ice, Cherenkov light is generated, primarily by the secondary positrons from inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$. While fine-grained detectors reconstruct individual neutrinos on an event-by-event basis, IceCube only picks up the average Cherenkov glow of the ice. To estimate the detection rate we follow Ref. [2], augmented with the latest IceCube efficiencies [3]. The complete detector will have 4800 optical modules (OMs) and the data are read out in 1.6384 ms bins, implying a total event rate of

$$R_{\bar{\nu}_e} = 186 \text{ bin}^{-1} L_{52} D_{10}^{-2} \langle E_{\nu_e}^3 \rangle/\langle E_{\nu_e}\rangle,$$

where $L_{52} = L_{\nu_e}/10^{52}$ erg s$^{-1}$, $D_{10} = D/10$ kpc and $E_{\nu_e} = E_{\nu_e}/15$ MeV.

The peak luminosity reaches $L_{52} = 2–5$ and at that time $\langle E_{\nu_e}\rangle \approx 15$ MeV. For a thermal or slightly pinched spectrum, $\langle E_{\nu_e}^3 \rangle/\langle E_{\nu_e}\rangle^3 = 2$. Altogether, we expect

$$R_{\bar{\nu}_e}^\text{max} = 1.5 \times 10^3 \text{ bin}^{-1}$$

as a typical peak event rate for a SN at 10 kpc. This signal is to be compared with a background of 280 s$^{-1}$ in each OM [2], corresponding for 4800 OMs to

$$R_0 = 2.20 \times 10^3 \text{ bin}^{-1}$$

with an rms fluctuation of 47 bin$^{-1}$. Therefore, the SN-induced “correlated noise” in the entire detector is highly significant [4, 5, 6]. From any one neutrino interacting in the ice, at most one Cherenkov photon is picked up: the signal counts are entirely uncorrelated.

The prompt $\nu_e$ burst immediately after bounce produces a peak rate of about 100 bin$^{-1}$, lasting for several ms. Its impact on the early count rate depends sensitively on the flavor oscillation scenario (see below).

III. EARLY NEUTRINO EMISSION

SN models suggest that neutrino emission for the first 20 ms after core bounce depends little on model assumptions or input physics [7], although beyond this early phase the accretion rate and therefore neutrino emission depends strongly, for example, on the progenitor mass profile. The prompt $\nu_e$ burst reaches its peak at 5–7 ms post bounce, which also marks the onset of $\bar{\nu}_e$ emission that is initially suppressed by the large $\nu_e$ chemical potential. Up to about 20 ms post bounce $L_{\nu_e}$ rises roughly linearly. We thus represent the early IceCube signal as [1]

$$R_{\nu_e} = \begin{cases} R_{\nu_e}^\text{max} \times 0 & \text{for } t < t_r, \\ 1 - e^{-(t-t_r)/\tau_r} & \text{for } t > t_r \end{cases}$$

where $t_r$ and $\tau_r$ are inferred from the IceCube signal.
with \( t_e = 6 \) ms, \( \tau_e = 50 \) ms and \( R_{\bar{\nu}_e}^{\text{max}} = 1.5 \times 10^3 \text{ bin}^{-1}. \) These parameters also provide an excellent fit to the first 100 ms of a numerical model from the Garching group that is available to us.

We may compare these assumptions with the early-phase models of Ref. [7]. \( L_{\bar{\nu}_e} \) rises nearly linearly to \( L_{\bar{\nu}_e} = 1.5-2 \) within 10 ms. The evolution of \( \left\langle E_{\bar{\nu}_e} \right\rangle_{\text{RMS}} = \left( \left\langle E_{\bar{\nu}_e}^3 \right\rangle / \left\langle E_{\bar{\nu}_e} \right\rangle \right)^{1/2} \) is also shown, a common quantity in SN physics that characterizes, for example, the efficiency of energy deposition: the IceCube rate is proportional to \( \left\langle E_{\bar{\nu}_e} \right\rangle_{\text{RMS}} \). At 10 ms after onset, \( \left\langle E_{\bar{\nu}_e} \right\rangle_{\text{RMS}} \) reaches 15 MeV, implying \( \left\langle E_{\bar{\nu}_e}^3 \right\rangle / \left\langle E_{\bar{\nu}_e} \right\rangle = 1 \). We thus estimate 10 ms after onset a rate of 280–370 bin \(^{-1}, \) to be compared with 270 bin \(^{-1}\) from Eq. (4). Therefore, our assumed signal rise is on the conservative side.

Of course, the early models do not fix \( \tau_e \) and \( R_{\bar{\nu}_e}^{\text{max}} \) separately; the crucial parameters are \( t_e \) and \( R_{\bar{\nu}_e}^{\text{max}} / \tau_e. \) The maximum rate that is reached long after bounce is not relevant for determining the onset of the signal.

If flavor oscillations swap the \( \bar{\nu}_e \) flux with \( \nu_x \) (some combination of \( \nu_\mu \) and \( \nu_\tau \)), the rise begins earlier because the large \( \nu_e \) chemical potential during the prompt \( \nu_e \) burst does not suppress the early emission of \( \nu_x \) [7]. Moreover, the rise time is faster, \( \left\langle E_{\bar{\nu}_e} \right\rangle_{\text{RMS}} \) larger, and the maximum luminosity smaller. We use Eq. (4) also for \( R_{\nu_x} \) with \( t_e = 0, \tau_e = 25 \) ms, and \( R_{\nu_x}^{\text{max}} = 1.0 \times 10^3 \text{ bin}^{-1}. \) Flavor oscillations are unavoidable and have been studied, for early neutrino emission, in Ref. [7]. Assuming the normal mass hierarchy, \( \sin^2 2\theta_{13} \gtrsim 10^{-3}, \) no collective oscillations, \(^1\) and a direct observation without Earth effects, Table I of Ref. [7] reveals that the \( \nu_e \) burst would be completely swapped and thus nearly invisible because the \( \nu_\mu, e^- \) elastic scattering cross section is much smaller than that of \( \nu_e. \) The survival probability of \( \bar{\nu}_e \) would be \( \cos^2 \theta_{12} \approx 2/3 \) with \( \theta_{12} \) the “solar” mixing angle. Therefore, the effective detection rate would be \( 2 \widetilde{R}_{\bar{\nu}_e} + \frac{1}{3} R_{\nu_x}. \) We use this case as our main example.

IV. RECONSTRUCTING THE SIGNAL ONSET

A typical Monte Carlo realization of the IceCube signal for our example is shown in Fig. 1. One can determine the signal onset \( t_0 \) within a few ms by naked eye. For a SN closer than our standard distance of 10 kpc, one can follow details of the neutrino light curve without any fit.

One can not separate the \( \bar{\nu}_e \) and \( \nu_x \) components for the example of Fig. 1. Therefore, we reconstruct a fit with a single component of the form Eq. (4), assuming the zero-signal background is well known and not fitted here. Using a time interval until 100 ms post bounce, we reconstruct \( t_0 = 3.2 \pm 1.0 \) ms (1σ). If we use only data until 33 ms post bounce we find \( t_0 = 3.0 \pm 1.7 \) ms. Indeed, if one fits Eq. (4) on an interval that ends long before the plateau is reached, we effectively fit a second order polynomial with a positive slope and negative second derivative at \( t_\tau, \) whereas the plateau itself is poorly fitted and its assumed value plays little role. Depending on the distance of the SN one will fit more or fewer details of the overall neutrino light curve and there may be more efficient estimators for \( t_\tau. \) Our example only provides a rough impression of what IceCube can do.

The reconstruction uncertainty of \( t_0 \) scales approximately with neutrino flux, i.e., with SN distance squared. The number of excess events above background marking the onset of the signal has to be compared with the background fluctuations. Therefore, a significant number of excess events above background requires a longer integration period if the flux is smaller, explaining this scaling behavior.

The interpretation of \( t_0 \) relative to the true bounce time depends on the flavor oscillation scenario realized in nature. This is influenced by many factors: The value of \( \theta_{13}, \) the mass ordering, the role of collective oscillation effects, and the distance traveled in the Earth. Combining the signal from different detectors, using future laboratory information on neutrino parameters, and perhaps the very coincidence with a gravitational-wave signal may allow one to disentangle some of these features. However, as a first rough estimate it is sufficient to say that the reconstructed \( t_0 \) tends to be systematically delayed relative to the bounce time by no more than a few ms. The statistical uncertainty of the \( t_0 \) reconstruction does not depend strongly on the oscillation scenario.
V. DISCUSSION

The authors of Ref. [1] used a SN emission model based on a two-component fit of the sparse SN 1987A data and described the overall neutrino signal in terms of several parameters which they say, after Eq. (5), are at odds with theoretical expectations. However, their parameter \(T_a = 2.4 \text{ MeV}\), describing the temperature of the neutrino-emitting gas during the accretion phase, gives \(\langle E_{\nu_e}\rangle = 5.2 T_a = 12.5 \text{ MeV}\) (see paragraph after Eq. 15 in the published version of Ref. [12]) and thus is virtually identical to the corresponding \(\langle E_{\nu_e}\rangle_{\text{RMS}}\) from Ref. [7] at 20 ms post bounce. In other words, while the SN 1987A implied \(\nu_e\) energies of Ref. [1] are lower than theoretical expectations for the overall accretion phase, in the absence of flavor oscillations they agree nicely with the models of Ref. [7] for the crucial first 20 ms. However, the chosen rise time \(\tau = 100 \text{ ms}\) is very long compared with the early-time models of Ref. [7].

In Ref. [7] the early neutrino signal after bounce was systematically studied for different input assumptions (progenitor mass, equation of state, neutrino opacities), leading to very similar results. On the other hand, one finds significantly different numerical examples in the literature. In Ref. [13] the \(\bar{\nu}_e\) luminosity rises to \(2 \times 10^{52} \text{ erg s}^{-1}\) after as much as 50 ms. In Ref. [14], a peak value of only \(1 \times 10^{52} \text{ erg s}^{-1}\) is reached and the rise within 10–20 ms after bounce is small. In Ref. [15] the \(\nu_e\) signal begins rising as late as 12 ms after the maximum of the \(\nu_e\) burst. There are many differences between these and other models in terms of numerical approach and input physics. It would be extremely useful if another group would investigate the early neutrino signal in the spirit of Ref. [7] for a range of physical assumptions, for different detector types and what can be learnt from a combined analysis. To this end it would be worthwhile if groups other than the Garching one would systematically study the numerical early-time neutrino signal to judge if indeed the dependence on physical assumptions is as small as found in Ref. [7].

In view of the large range of possible distances to the next nearby SN and concomitant flux differences, these uncertainties do not change our overall conclusions. In our fiducial example IceCube can reconstruct the signal onset within \(\pm 6–7 \text{ ms}\) at 1\(\sigma\) CL for a SN at 20 kpc, comparable to what Ref. [1] found for Super-Kamiokande. Ideally, of course, one would combine the measurements from several detectors.

A gravitational wave measurement of the core bounce in coincidence with neutrino onset would be of obvious astrophysical importance. In addition one could test the weak equivalence principle. Both neutrinos and gravitational waves should suffer the same Shapiro time delay in the gravitational potential of the galaxy. For SN 1987A in the Large Magellanic Cloud, this delay was a few months. The coincidence of the neutrino burst with the rise of the light curve within a few hours proved an equal Shapiro delay for photons and neutrinos to within about \(10^{-3}\) [16, 17]. A millisecond-scale coincidence between neutrinos and gravitational waves would extend and refine this test, in detail depending on the location of the SN.

If the SN can not be located by astronomical means because of obscuration, the electron-recoil signal in Super-Kamiokande or a future megatonne water Cherenkov detector is the method of choice [18, 19], whereas arrival-time triangulation was dismissed. With IceCube almost complete, the situation has changed and triangulation can play a useful role after all, at least for a not-too-distant SN. Moreover, in Europe a big detector of the LAGUNA-class [20] may become available (representing one of three possible large-scale detector types) and a megatonne water-Cherenkov detector may be built in North America. Arrival-time triangulation between large-scale neutrino detectors on different continents could become viable.

It would be a worthwhile exercise to study the possibilities of bounce timing, based on common astrophysical assumptions, for different detector types and what can be learnt from a combined analysis. To this end it would be worthwhile if groups other than the Garching one would systematically study the numerical early-time neutrino signal to judge if indeed the dependence on physical assumptions is as small as found in Ref. [7].

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