Detection of Neutrinos from Supernovae in Nearby Galaxies

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(Received 15 March 2005; published 18 October 2005)

While existing detectors would see a burst of many neutrinos from a Milky Way supernova, the supernova rate is only a few per century. As an alternative, we propose the detection of $\sim$1 neutrino per supernova from galaxies within 10 Mpc, in which there were at least 9 core-collapse supernovae since 2002. With a future 1 Mton scale detector, this could be a faster method for measuring the supernova neutrino spectrum, which is essential for calibrating numerical models and predicting the redshifted diffuse spectrum from distant supernovae. It would also allow a $\gtrsim 10^4$ times more precise trigger time than optical data alone for high-energy neutrinos and gravitational waves.

DOI: 10.1103/PhysRevLett.95.171101 PACS numbers: 97.60.Bw, 13.15.+g, 25.30.Pt, 95.55.Vj

One of the unsolved problems of astrophysics is how core-collapse supernovae explode. Nuclear fusion reactions in the core of a massive star produce progressively heavier elements until a Chandrasekhar mass of iron is formed, and electron degeneracy pressure cannot support the core under the weight of the stellar envelope. The core collapses until it reaches nuclear densities and neutrino emission begins; then an outgoing bounce shock should form, unbinding the envelope and producing the optical supernova. While successful in nature, in most numerical supernova models, the shock stalls, so that the fate of the entire star is to produce a black hole (after substantial neutrino emission), but no optical supernova.

Since the gravitational energy release transferred to neutrinos, about 3×10^{53} erg, is $\sim$100 times greater than the required kinetic energy for the explosion, it is thought that neutrino emission and interactions are a key diagnostic or ingredient of success. However, not enough is directly known about the total energies and temperatures of the neutrino flavors. The $\simeq 20$ events from SN 1987A were only crudely consistent with expectations for $\bar{\nu}_e$, and gave very little information on the other flavors [1]. It is thus essential to collect more supernova neutrino events. A Milky Way supernova would allow detailed measurements, but the supernova rate is only a few per century. If the Super-Kamiokande detector were loaded with $GdCl_3$ [2], the diffuse supernova neutrino background (DSNB) [3–5] could be cleanly detected, probing the supernova neutrino spectrum, but convolved with the rapidly evolving star formation rate [6] up to redshift $z \simeq 1$.

We propose an intermediate regime, in which the number of events per supernova is $\sim$1, instead of $\gg 1$ (Milky Way) or $\ll 1$ (DSNB), motivated by the serious consideration of 1 Mton scale water-Čerenkov detectors in Japan (Hyper-Kamiokande [7]), the United States (UNO [8]), and Europe (MEMPHYS [9]). These detectors, which may operate for decades, are intended for proton decay and long-baseline accelerator neutrino oscillation studies, but could also detect neutrinos from Milky Way supernovae, a point that has attracted much interest [10]. The distance range of a 1 Mton detector is about 10 Mpc, within which the calculated supernova rate is about one per year, as shown in Fig. 1. Since the number of events per supernova is small, background rejection requires a coincidence of at least two neutrinos or one neutrino and an optical (or other waveband) supernova.

Supernova neutrino detection.—For a Milky Way supernova at 10 kpc, the expected number of events in

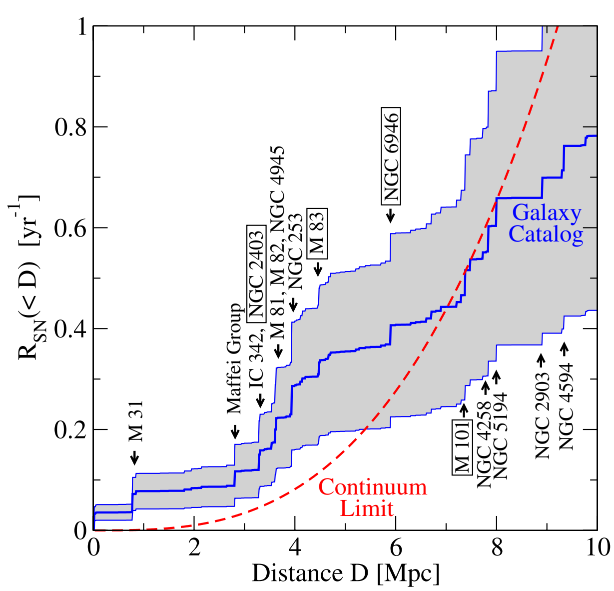

FIG. 1 (color online). Cumulative calculated core-collapse supernova rate versus distance. The dashed line is the continuum limit using the GALEX $z = 0$ star formation rate [6]. For our particular local volume, and its fortuitous enhancement, we use a galaxy catalog [11]; the stepped line is based on star formation rates for individual galaxies, and the band is the uncertainty. Some major galaxies are indicated, and those in boxes have especially high optical supernova rates (see Table I).

the Super-Kamiokande detector (22.5 kton) is $\sim 10^4$, corresponding to 1 event at 1 Mpc, 0.1 events at 3 Mpc, and so on. For an expected number of events μ, the Poisson probability to detect n events is $P_n = \mu^n e^{-\mu}/n!$; for small μ, we scale $P_1 \simeq \mu$ by the number of supernovae. As shown in Fig. 2, for each supernova within, say, 4 Mpc, the chance of detecting a single neutrino (or a background event; see below) in the Super-Kamiokande detector is $\sim$3%. While small, this should motivate a careful analysis of their data.

To make this technique more efficient, detectors larger than the Super-Kamiokande detector are needed. We consider a similar detector with a 1 Mton fiducial volume, which is somewhat larger than the proposed detectors, but if two are built, the combined mass could exceed 1 Mton. In Fig. 2, we show the detection probabilities for at least one or two events from a single supernova versus distance, along with the calculated supernova rate, which coincidentally also varies from 0 to 1. For a 1 Mton detector, both the detection probability per supernova and the relevant supernova rate are quite favorable, so that the supernova neutrino spectrum could be constructed, slowly but (almost) steadily. Additionally, the detection of even a single neutrino could fix the start time of the supernova to $\sim$10 s instead of $\sim$1 day, greatly reducing backgrounds for observing prompt gravitational wave or high-energy neutrino emission. Calculations of the nearby supernova rate and background rejection capabilities are needed, and we turn to these next.

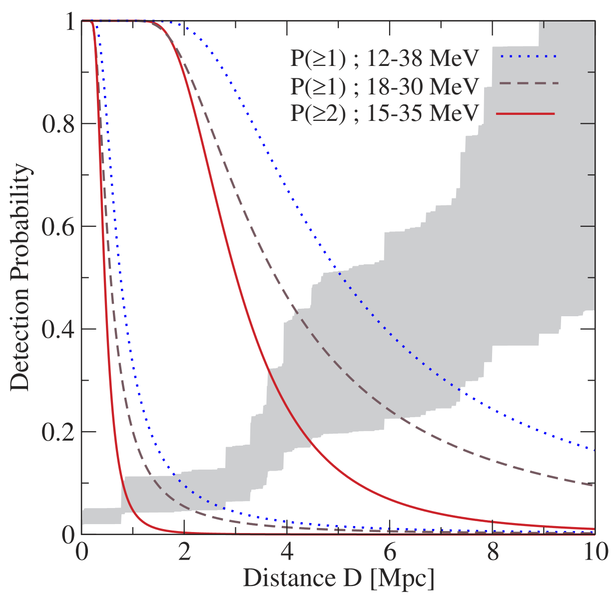

FIG. 2 (color online). Probability of detecting at least one (dotted and dashed curves) or at least two (solid curves) supernova neutrinos versus distance. Background considerations restrict the useful energy intervals, labeled here, and explained in the text. The upper set of curves is for a 1 Mton detector, and the lower set for the 22.5 kton Super-Kamiokande detector; for another detector size, scale the distance to compensate. The shaded band indicates the calculated cumulative supernova rate. The probabilities for single background events are $\simeq$0.4 (1 Mton) and $\simeq$ 0.02 (Super-Kamiokande detector), independent of distance.

Nearby supernova rate.—The supernova rate within a typical sphere of radius 10 Mpc can be calculated using the $z = 0$ limit of the measured star formation rate, for which we use the latest dust-corrected measurements from GALEX [6] (other recent measurements are in agreement). We convert this to a core-collapse supernova rate using the stellar initial mass function to calculate the fraction of stars above $8M_\odot$; the result is in good agreement with the measured core-collapse supernova rate versus redshift, as shown in Ref. [5]. Our "continuum limit" result is shown in Fig. 1. Since galaxies are clustered and have varying supernova rates, our local volume may differ from a typical volume. It does, and, in fact, the nearby supernova rate is higher than typical. We used the recent catalog of Ref. [11] to obtain galaxy distances, morphological types, and optical luminosities, and then the conversion factors of Ref. [12] to calculate the supernova rate for each galaxy; our "galaxy catalog" result is also shown in Fig. 1 (see also Ref. [13]). Most of the uncertainty comes from the conversion between galaxy properties and supernova rates, and could be substantially reduced by direct measurements of the star formation rates for these specific galaxies.

The calculated core-collapse supernova rate within 10 Mpc is about one per year; this arises both from many galaxies similar to the Milky Way and from several indicated galaxies with higher rates (Table I lists galaxies with especially high historical supernova rates). Our calculations are based on *star formation* rates, which should predict *supernova* rates (type Ia supernovae, which do not have substantial neutrino emission, are only about 15% of supernovae). If there were bursts of star formation on time scales less than the lifetimes of massive stars, these results could differ. Quite recently, due to a rise in the quantity and quality of supernova searches, the number of discovered supernovae has increased very dramatically [14], strongly suggesting that the calculated and historical supernova rates are significant underestimates. Since 2002, there were at least 9 nearby core-collapse supernovae: the 4 given in Table I plus 2004am (3.5 Mpc), 2005af (3.6 Mpc), 2002ap and 2003gd (both 7.3 Mpc), and 2002bu (about 7.5 Mpc). The observed numbers of 9 within 10 Mpc (2.8 expected) and 4 within 4 Mpc (1.0 expected) indicate that the true nearby supernova rates are probably about 3 times higher than in our calculation, which we regard as quite conservative.

Neutrino-neutrino coincidence detection.—For a supernova in M 31, the yield in a 1 Mton detector would be high (about 50 events, over all energies). However, the total nearby supernova rate remains small until a distance of about 4 Mpc is reached, and then the number of detected neutrinos per supernova is much smaller. Thus we first consider the case in which at least two candidate supernova neutrino events are detected within 10 s, the supernova neutrino emission time scale. In Fig. 3, we show the

TABLE I. Selected nearby galaxies with high supernova rates.

Galaxy	D (Mpc)	Known supernovae
NGC 2403	3.3	1954J, 2002kg, 2004dj
NGC 5236 (M 83)	4.5	1923A, 1945B, 1950B, 1957D, 1968L, 1983N
NGC 6946	5.9	1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et
NGC 5457 (M 101)	7.4	1909A, 1951H, 1970G

expected neutrino signal in a 1 Mton detector for a supernova at 4 Mpc, using emission and oscillation parameters similar to those in Ref. [3]; the 1 day backgrounds shown should be ignored here. For other reasonable choices of supernova neutrino temperatures and oscillation scenario (i.e., an inverted hierarchy), the signal could be significantly larger. The detection reaction is $\bar{\nu}_e + p \rightarrow e^+ + n$, for which the visible positron energy is nearly the full neutrino energy [15].

The rate of accidental background coincidences within 10 s is small, based on Super-Kamiokande detector data on spallation daughter decays [16] and invisible (sub-Čerenkov) muon decays [17]. We estimate these singles rates for a 1-Mton detector as $\lesssim 650\ \mathrm{yr}^{-1}$ above 15 MeV and $\lesssim 400\ \mathrm{yr}^{-1}$ below 35 MeV, respectively. The total accidental coincidence rate is thus $\lesssim 2(1050\ \mathrm{yr}^{-1})^2 \times (10\ \mathrm{s}) = 0.7\ \mathrm{yr}^{-1}$, scaling as the detector mass squared, and concentrated near the chosen energy range boundaries (15–35 MeV). The separation of signal and background events could easily be improved, using the full energy and time distributions of events. With at least two neutrinos detected, a supernova could be identified without optical confirmation, so that the start of the light curve could be forecasted by a few hours, along with a short list of probable host galaxies. This would also allow the detection of supernovae that are either heavily obscured by dust (e.g., in the starburst galaxies M 82 and NGC 253) or are optically dark due to prompt black hole formation. If an optical supernova is found, even with crude timing information, this would greatly reduce background rates.

Neutrino-optical coincidence detection.—To extend the reach to greater distances, we also consider the case in which only one neutrino is detected, but a counterpart optical supernova can be identified. Although core-collapse supernova light curves show a great deal of variation, we assume that it will be possible to identify the start time of the core collapse to within $\Delta t = 1$ day by optical techniques alone, at least for nearby supernovae, which can be found very early. In this case, only the detector singles background rates are relevant, and these scale with detector mass. In Fig. 3, we show the spectrum for the invisible muon background; nuclear gamma cuts are assumed in the case of pure water, and also neutron cuts in the case of added $GdCl_3$ [2]. The lower limits of the energy intervals used in Fig. 2 are defined by large spallation and solar neutrino backgrounds (pure water) and reactor backgrounds (with added $GdCl_3$).

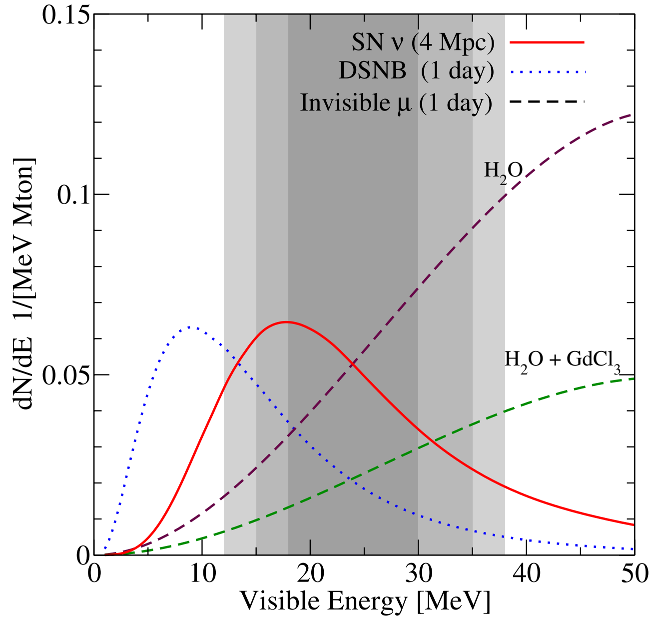

FIG. 3 (color online). Spectrum of detected supernova neutrinos ($D = 4$ Mpc) in a 1 Mton detector. The backgrounds shown are relevant for a neutrino-optical coincidence, and are reduced for a neutrino-neutrino coincidence. The shaded bands indicate the energy intervals for signal selection (see Fig. 2); at low energies, other backgrounds (not shown) are very large.

When an optical supernova is found, and its distance and start time uncertainty Δt identified, the neutrino data in the appropriate energy interval can be checked. Assuming that an optical supernova is detected about once per year, the 1 day window reduces the singles backgrounds by a factor of 365. Using Fig. 3, one can estimate the probability that a neutrinolike event within a 1 day interval of an optical supernova was more likely signal or background. In 18–30 MeV, the numbers of signal and background events expected are $N_\nu^{\mathrm{H_2O}} = 10 D_{\mathrm{Mpc}}^{-2} V_{\mathrm{Mton}}$ and $N_{\mathrm{bg}}^{\mathrm{H_2O}} = 0.9 \Delta t_{\mathrm{day}} V_{\mathrm{Mton}}$; in 12–38 MeV, they are $N_\nu^{\mathrm{Gd}} = 19 D_{\mathrm{Mpc}}^{-2} V_{\mathrm{Mton}}$ and $N_{\mathrm{bg}}^{\mathrm{Gd}} = 1.2 \Delta t_{\mathrm{day}} V_{\mathrm{Mton}}$. If one event is detected in association with an optical supernova, the probability that it is real is $P_\nu/(P_\nu + P_{\mathrm{bg}})$, using the Poisson probabilities for one event corresponding to N_ν and N_{bg}. At larger distances, the signal per supernova decreases as $1/D^2$, but the supernova frequency increases as D^3. Since the detector background rates are constant with D, the range cannot be extended unless Δt can be reduced, due to accidental coincidences.

Discussion and conclusions.—We have proposed a new method for measuring the supernova neutrino spectrum and for improving the observational characterization of nearby core-collapse supernovae. With a 1 Mton detector, supernova neutrinos could be collected at a relatively brisk rate. Considering just the galaxies within 4 Mpc, and multiplying the supernova rate, the neutrino multiplicity, and the neutrino detection probability (assuming added $GdCl_3$), we obtain $0.3 \times 2 \times 0.25 \simeq 0.15$ and $0.3 \times 1 \times 0.4 \simeq 0.12$ neutrinos per year in the double and single detection modes, respectively. However, since the calculated supernova rates seem to be too conservative by a factor of about 3, the total neutrino detection rates could be as large as one per year. The background rates are comparable, but it should be possible to reduce their impact with a more sophisticated analysis.

With the exception of SN 1987A in the Large Magellanic Cloud, a close companion of the Milky Way, no neutrino source beyond the Sun has been detected yet. But besides the excitement of detecting neutrinos from beyond 1 Mpc, and confirming core-collapse supernova neutrino emission, there are quantitative reasons that detecting extragalactic supernova neutrinos even one at a time would be important.

Measurement of the supernova neutrino spectrum.—The $\simeq 20$ events from SN 1987A show statistically significant disagreements with the predicted emission spectrum, and between detectors [1]. A comparable number of events collected in new detectors could resolve these issues and impact supernova *r*-process nucleosynthesis calculations [18]. These data would also average over many supernovae, which is useful if the emission per supernova is less uniform than expected, due to variation in the properties and fates of the collapsed cores. The $z = 0$ emission spectrum could refine calculations of the redshift-integrated DSNB flux, and the contribution of the harder nearby spectrum removed. Since a typical distance is about 100 times greater than for SN 1987A, limits on neutrino decay lifetimes could be correspondingly improved. With each optical supernova providing the neutrino direction, one could test the expected local galaxy clustering, the neutrino-positron angular distribution [15], and possibly neutrino mixing effects in Earth.

A precise time trigger for other supernova signals.—We have assumed that the start time of a nearby core-collapse supernova can be determined to about 1 day using optical data alone. This is somewhat optimistic, though there is renewed interest in fully characterizing the nearby core-collapse supernova rates and optical emission. For example, the Caltech Core-Collapse Project is designed to extensively study 50 nearby core-collapse supernovae, in part to explore the supernova–gamma-ray burst connection [19]. Early supernova discoveries by amateurs may also be helpful. The detection of even a single neutrino in association with a nearby supernova would reduce the uncertainty on the start time from $\sim$1 day to $\sim$10 s. This precise trigger time could greatly reduce backgrounds for more speculative types of prompt supernova emission, e.g., gravitational waves [13,20] and high-energy neutrinos [21,22].

We thank D. DePoy, A. Gould, R. Pogge, and M. Vagins for discussions. This work was supported by The Ohio State University. S. A. was supported by a Grant-in-Aid from JSPS, and H. Y. was supported by NSF Grant No. PHY-0244384 at the University of Wisconsin, and by the Wisconsin Alumni Research Foundation.

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