Detection of Neutrinos from Supernovae in Nearby Galaxies

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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.

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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 \( 3 \times 10^{53} \) 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 \( \sim 20 \) 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 Super-Kamiokande were loaded with GdCl₃ [2], the diffuse supernova neutrino background (DSNB) [3, 4, 5] could be cleanly detected, probing the supernova neutrino spectrum, but convolved with the rapidly evolving star formation rate [6]. Some major galaxies are indicated, and those in boxes have especially high optical supernova rates (see Table I).

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 which 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 Super-Kamiokande (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 $\mu$, the Poisson probability to detect $n$ events is $P_n = \mu^n e^{-\mu}/n!$; for small $\mu$, 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 Super-Kamiokande is $\sim 3\%$. While small, this should motivate a careful analysis of their data.

To make this technique more efficient, detectors larger than Super-Kamiokande 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 $\sim 10$ seconds 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.

**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 [8] (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 $8 M_{\odot}$: the result is in good agreement with the measured core-collapse supernova rate versus redshift, as shown in Ref. [8]. 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. [12]). Most of the uncertainty comes from the conversion between galaxy properties and supernova rate, 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, as well as several indicated galaxies with higher rates (Table II 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 timescales 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 II 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 can-


**TABLE I: Selected nearby galaxies with high supernova rates.**

| Galaxy            | D [Mpc] | Known Supernovae        |
|-------------------|---------|-------------------------|
| NGC 2403          | 3.3     | 1954A, 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     |

Candidate supernova neutrino events are detected within 10 seconds, the supernova neutrino emission timescale. In Fig. 3, we show the 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 temperature and oscillation daughter decays [15] and invisible (sub-ˇCerenkov) neutrino fluxes, the signal could be significantly larger. The detection rate is \( \nu_e + p \rightarrow e^+ + n \), for which the visible positron range is nearly the full neutrino energy [17].

The rate of accidental background coincidences within 10 s is small, based on Super-Kamiokande data on spallation daughter decays [15] and invisible (sub-ˇCerenkov) muon decays [16]. We estimate these singles rates for a 1-Mton detector as \( \lesssim 650 \text{ yr}^{-1} \) above 15 MeV and \( \lesssim 400 \text{ yr}^{-1} \) below 35 MeV, respectively. The total accidental coincidence rate is thus \( \lesssim 2 \times (1050 \text{ yr}^{-1})^2 \times (10 \text{ s}) = 0.7 \text{ yr}^{-1} \), 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 which 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 \( \Delta t = 1 \text{ day} \) 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 GdCl₃. 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 GdCl₃).

When an optical supernova is found, and its distance and start time uncertainty \( \Delta t \) 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 365. Using Fig. 2, one can estimate the probability that a neutrino-optical 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 \( N_{\nu}^{H_2O} = 10 D_{Mpc}^{-2} V_{Mton} N_{\nu}^{H_2O} = 0.9 \Delta t_{day} V_{Mton} \) in 12–38 MeV, they are \( N_{\nu}^{Gd} = 19 D_{Mpc}^{-2} V_{Mton} N_{bg} = 1.2 \Delta t_{day} V_{Mton} \). If one event is detected in association with an optical supernova, the probability that it is real is \( P_{\nu}/(P_{\nu} + P_{bg}) \), using the Poisson probabilities for one event corresponding to \( N_{\nu} \) 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 \( \Delta t \) 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 characteriza-
tion of nearby core-collapse supernovae. With a 1-Mton
detector, supernova neutrinos could be collected at a re-
latively brisk rate. Considering just the galaxies within
4 Mpc, and multiplying the supernova rate, the neutrino
multiplicity, and the neutrino detection probability (as-
suming added GdCl$_3$), we obtain $0.3 \times 2 \times 0.25 \approx 0.15$
and $0.3 \times 1 \times 0.4 \approx 0.12$ neutrinos per year in the double
and single detection modes, respectively. However, since
the calculated supernova rates seem to be too conserva-
tive 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 Mag-
ellenic 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 de-
tecting extragalactic supernova neutrinos even one at a
time would be important:

- **Measurement of the supernova neutrino spectrum:**
The $\approx 20$ events from SN 1987A show statistically sig-
nificant disagreements with the predicted emission spec-
trum, 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 su-
ernova is less uniform than expected, due to variation
in the properties and fates of the collapsed cores. The
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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,
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- **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 characteriz-
ing 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 [16]. Early supernova dis-
coversies by amateurs may also be helpful. The detection
of even a single neutrino in association with a nearby su-
ernova would reduce the uncertainty on the start time
from $\sim 1$ day to $\sim 10$ seconds. 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].

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