TOMOGRAPHY OF MASSIVE STARS FROM CORE COLLAPSE TO SUPERNOVA SHOCK BREAKOUT

MATTHEW D. KISTLER1,3, W. C. HAXTON1, and HASAN YÜKSEL2

1 Lawrence Berkeley National Laboratory and Department of Physics, University of California, Berkeley, CA 94720, USA
2 Theoretical Division, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Received 2012 December 13; accepted 2013 October 10; published 2013 November 6

ABSTRACT

Neutrinos and gravitational waves are the only direct probes of the inner dynamics of a stellar core collapse. They are also the first signals to arrive from a supernova (SN) and, if detected, establish the moment when the shock wave is formed that unbinds the stellar envelope and later initiates the optical display upon reaching the stellar surface with a burst of UV and X-ray photons, the shock breakout (SBO). We discuss how neutrino observations can be used to trigger searches to detect the elusive SBO event. Observation of the SBO would provide several important constraints on progenitor structure and the explosion, including the shock propagation time (the duration between the neutrino burst and SBO), an observable that is important in distinguishing progenitor types. Our estimates suggest that next-generation neutrino detectors could exploit the overdensity of nearby SNe to provide several such triggers per decade, more than an order-of-magnitude improvement over the present.

Key words: neutrinos – stars: massive – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Core-collapse supernova (SN) observations have improved rapidly in quantity and quality over the past decade, and with the coming large synoptic surveys, rates should soon advance by an additional two orders of magnitude or more, with \( \sim 10^3 \) events per year likely to be found within \( z \sim 0.5–1 \) (Lien & Fields 2009). With the new data has come a greater appreciation of the variety of stellar evolutionary phenomena leading to these events. These include a wide range of possibilities associated with the loss/modification of the envelope. For very massive stars, these include strong outbursts occurring within a few years prior to the collapse (Pastorello et al. 2007; Mauerhan et al. 2013; Ofek et al. 2013; Fraser et al. 2013) and circumstellar interactions during the SN (Gal-Yam 2012), while premortem enshrouding by dust has been seen in lower-mass stars near the core-collapse threshold (Prieto et al. 2008; Thompson et al. 2009). The prevalence of binary evolution suggests that mass transfer could play a role prior to a substantial fraction of collapses (Sana et al. 2012). However, we have not found signatures of impending core collapse that are useful observationally—which would allow us to find and study stars within a designated time before collapse.

A successful core-collapse SN requires the ejection of the remaining stellar envelope by an outward-propagating shock wave that originates deep within the star’s core, where it can be boosted initially by neutrino heating of the matter behind the shock front. The radiative precursor—the first radiation to “leak out” ahead of the shock front, marking the beginning of shock breakout (SBO), a burst of UV/soft X-ray photons—appears when the shock front reaches a point in the star’s envelope where the optical depth \( \tau \sim 25 \sim c / v_{\text{shock}} \) (Colgate 1968; Falk & Arnett 1977; Klein & Chevalier 1978). The SBO grows in luminosity, peaking at \( \tau \sim 1 \) and producing an integrated energy release in radiation of \( \sim 10^{46–49} \text{erg} \) (e.g., Ensmann & Burrows 1992).

The SBO contains a great deal of information about the exploding star (e.g., Matzner & McKee 1999). However, obtaining quality data from such events is exceedingly difficult, since the SBO is the first detectable photon signal to arrive from an SN and has a duration of only seconds to hours (depending on the progenitor), much less than the time that an SN is bright optically. Further, Earth’s atmosphere is opaque to the SBO spectral peak, and space telescopes cannot typically observe more than one nearby galaxy at a time.

To observe an SBO at present requires either observations of deep fields or a great deal of luck. Observations of distant SNe with limited sampling of light curves can be open to interpretation, such as an SN at \( z \approx 0.185 \) detected by Galaxy Evolution Explorer, for which Schawinski et al. (2008) claimed that the SBO was seen, while Gezari et al. (2008) concluded otherwise. The detection of a soft X-ray burst preceding SN 2008D, interpreted as an SBO from a dense Wolf–Rayet (W-R) wind by Soderberg et al. (2008), was due to serendipitous Swift observations of the host galaxy as the star exploded, an exceptional circumstance.

We discuss the possibility of mitigating these difficulties by exploiting the two early signals of core collapse available to observers, neutrinos and gravitational waves (Marek et al. 2009; Yakunin et al. 2010; Ott et al. 2012), concentrating on the former. We discuss two strategies, each with positive and negative attributes. The first, a Galactic SN, would produce an unambiguous signal in neutrino detectors today (see Ikeda et al. 2007; Abbasi et al. 2011; Scholberg 2012) that could be combined with SBO data to constrain properties of the collapsing star, but it suffers from an unfavorable event rate of \( \sim 1 \) per century.

The second, and our main focus here, is SNe within nearby galaxies. A number of studies have confirmed the feasibility of water Cerenkov detectors in the \( \sim 0.5–1 \) Mton range, and serious efforts to proceed with such neutrino detectors within a decade have been made around the world (Abe et al. 2011; LBNE Collaboration 2012; Autiero et al. 2007). As these will have a reach of a few Mpc (see Figure 1), their SN detection rates can exceed one per decade. A multi-Mton instrument would increase this to nearly one event per year. Two techniques to reach a \( \sim 5 \) Mton mass have been put forward. Both employ strategies to provide the overburden required to adequately
suppress cosmogenic backgrounds, without excavating a mountain of rock. The DeepTITAN D concept, addressed in Suzuki (2001) and Kistler et al. (2011), is based on large tanks of pure water submerged beneath the sea, while the IceCube Collaboration (2011) has discussed a densely instrumented array in south pole ice within IceCube.

Detection of both the neutrino burst and the SBO would determine the shock propagation time, placing an important new constraint on progenitor star properties. Even if directional information from the neutrinos is insufficient to isolate the source—which would likely be the case—we find that the candidate SN host galaxies would be limited in number, so that targeted campaigns could be launched to discover the UV/X-ray burst from the SBO using conventional methods. We also discuss searches for below-threshold neutrino counts in the event that non-triggered SBO surveys prove successful, the combination of which would achieve the same end. The distance range covered by this technique also coincides well with surveys that are imaging prospective SN progenitors. Connecting the SN/SBO event with pre-explosion optical images would further improve our characterization of the star, with important implications for better understanding SN morphologies.

2. BREAK ON THROUGH

Observational efforts to measure the progression of the SN shock wave from the stellar core to surface will require neutrino or gravitational wave measurements of the collapse in conjunction with techniques to capture the SBO signal that follows after a delay that varies from star to star. As motivation, we first discuss the relationship of the propagation time to the SBO observables addressed by Matzner & McKee (1999). There are four dimension-full scales that arise when dealing with an adiabatic, radiation-dominated, and non-gravitating explosion: the explosion energy $E_{\text{ej}}$, the core mass $M_{\text{NS}}$, the ejected mass $M_{\text{ej}} = M_* - M_{\text{NS}}$, and the progenitor star’s radius $R_*$. Here $M_* = M_{\text{ej}} + M_{\text{NS}}$ is the total mass. We describe below the functional dependences of SBO observables on these four scales in simple polytrope models.

Matzner & McKee (1999) discussed three observables connected with shock emergence: the post-shock radiation temperature $T_{\text{se}}$, the SBO energy $E_{\text{se}}$, and the timescale for radiation to diffuse out of the shock $t_{\text{se}}$ (for non-relativistic ejecta). These were evaluated in the context of an analytical model, a progenitor whose envelope can be represented as a polytrope. They provided results for $n = 3/2$ and $n = 3$ polytropes, with the latter yielding

\[
T_{\text{se}} = 1.31 \times 10^6 \kappa \left( \frac{0.34 \text{ cm}^2 \text{g}^{-1}}{\rho_1} \right)^{\frac{1}{1.046}} \left( \frac{M_{\text{ej}}}{10 M_\odot} \right)^{-0.14} \left( \frac{R_*}{50 R_\odot} \right)^{-0.48},
\]

\[
E_{\text{se}} = 7.6 \times 10^{46} \kappa \left( \frac{0.34 \text{ cm}^2 \text{g}^{-1}}{\rho_1} \right)^{-0.84} \left( \frac{M_{\text{ej}}}{10 M_\odot} \right)^{-0.42} \left( \frac{R_*}{50 R_\odot} \right)^{1.68},
\]

\[
t_{\text{se}} = 40 \left( \frac{0.34 \text{ cm}^2 \text{g}^{-1}}{\rho_1} \right)^{0.45} \left( \frac{M_{\text{ej}}}{10 M_\odot} \right)^{0.27} \left( \frac{R_*}{50 R_\odot} \right)^{1.90}.
\]

Here $\kappa$ is the opacity, and the density ratio $\rho_1/\rho_*$ can be related to the ratio of $M_*/M_{\text{ej}}$ by a coefficient that depends on the polytrope, e.g.,

\[
\frac{\rho_1}{\rho_*} \equiv \frac{R_*^3}{M_{\text{ej}}} \left( \frac{G M_*}{(n + 1) K R_*} \right)^n \rightarrow 0.324 \frac{M_*}{M_{\text{ej}}},
\]

where $K$ is the equation-of-state parameter, $p_0 = K \rho_0^{(n+1)/n}$. One motivation for the work of Matzner and McKee was to relate observables connected with the SBO and expanding ejecta with parameters characterizing the progenitor’s structure and the explosion, $M_{\text{ej}}$, $R_*$, and $E_{\text{in}}$.

The present study of the shock wave propagation time, defined here as

\[
\Delta t = t_{\text{sBO}} - t_{\text{CC}} = \int_{R_{\text{NS}}}^{R_*} \frac{dr}{v_*(r)},
\]

has a similar motivation. An analytic form for the shock velocity $v_*(r)$ that accounts for acceleration due to the sweeping up of enclosed envelope mass, $m(r)$, and the declining density gradient, $\rho_0(r)$, was given by Matzner & McKee (1999); who showed that the formula nicely reproduces numerical velocity profiles, as can be seen from Figure 2 of their paper). With this substitution in Equation (3), $\Delta t$ becomes

\[
\Delta t = 1.26 \int_{R_{\text{NS}}}^{R_*} dr \left[ \frac{m(r)}{E_{\text{in}}} \right]^{1/2} \left[ \frac{\rho_0(r)}{m(r)} \right]^{-0.19}.
\]
While we will evaluate this for specific progenitors below, we can make contact with Matzner & McKee (1999) by calculating Δτ for polytropes, to illustrate its functional dependence on progenitor properties. In Matzner & McKee (1999) the polytrope could be restricted to the envelope, in which case the Lane–Emden equation reduces to a first-order equation with a boundary condition at the inner surface of the envelope. In contrast, as Δτ involves an integral over most of the star, here a polytrope is a more aggressive approximation. We find for

\[ n = 3 \text{ and } 3/2 \]

\[
\Delta n = 6851 \left( \frac{10^{51} \text{ erg}}{E_{\text{in}}} \right)^{1/2} \left( \frac{M_{\text{ej}}}{10 M_\odot} \right)^{1/2} \left( \frac{R_\odot}{50 R_\odot} \right) \times \left[ 1 - 0.407 \left( \frac{M_{\text{NS}}}{M_{\text{ej}}} \right)^{0.81} + 0.285 \left( \frac{M_{\text{NS}}}{M_{\text{ej}}} \right)^{1.12} \right].
\]

\[
\Delta \text{HIB} = 7226 \left( \frac{10^{51} \text{ erg}}{E_{\text{in}}} \right)^{1/2} \left( \frac{M_{\text{ej}}}{10 M_\odot} \right)^{1/2} \left( \frac{R_\odot}{50 R_\odot} \right) \times \left[ 1 - 0.738 \left( \frac{M_{\text{NS}}}{M_{\text{ej}}} \right)^{0.80} + 0.467 \left( \frac{M_{\text{NS}}}{M_{\text{ej}}} \right)^{1.20} \right].
\]

(5)

These two results are very similar, which perhaps suggests relatively little sensitivity to polytrope index or variations of that index that might be appropriate for different portions of the star. The factors in the square brackets are fits to numerical results and are very accurate representations of the dependence of Equation (4) on \( R_{\text{NS}} \). Deep interiors of core-collapse SNe are often described as \( n = 3 \) polytropes, as this corresponds to a relativistic electron gas equation of state. As discussed in Matzner & McKee (1999), \( n = 3 \) is appropriate for the radiative envelopes of blue supergiants (BSGs), but a better fit to models for the inner 75% of the mantle (by mass) is obtained with an effective index \( n \sim 2.1–2.4 \).

We have also evaluated Equation (4) directly from progenitor models. Figure 2 shows the resulting propagation times for an 11–30 \( M_\odot \) range of non-rotating red supergiant (RSG) progenitors from Woosley et al. (2002), as well as 12 and 16 \( M_\odot \) BSG and 16 and 35 \( M_\odot \) W-R star models from Woosley & Heger (2006), with the inner 1.4 \( M_\odot \) forming a neutron star. We have used \( E_{\text{in}} = 0.5 \times 3 \times 10^{51} \text{ erg} \) to bracket the canonical \( 10^{51} \text{ erg} \). The polytrope results yield propagation times that generally agree to within \( \sim 10\%–20\% \).

The convective RSG envelopes extend up to \( \sim 1500 R_\odot \), while BSG radii are typically limited to \( \sim 25 R_\odot \). From the polytrope results one expects propagation times to be proportional to radii, and Figure 2 shows the expected gap of \( \sim 50 \) between RSG and BSG times. In W-R stars, thought to give rise to Type Ib/Ic SNe (\( \sim 10\%–20\% \) of all SNe), the shock arrives at the surface very quickly, as the strong winds in such stars lead to complete loss of their envelopes. As the SBO timescale is comparable to that of neutrino emission, little early warning would be available, although an optically thick wind may delay emergence (e.g., Balberg & Loeb 2011; Chevalier & Irwin 2012).

While observing the SBO spectrum and light curve would provide several pieces useful for a forensic study of the departed star (see Calzavara & Matzner 2004), timing alone would suggest a type and mass. An illustrative example of the utility of this feature is in settling disagreements in mass estimates provided by hydrodynamic SN modeling and pre-SN progenitor imaging. SN 2004et, for instance, originated in NGC 6946, within range of a 5 Mton detector. As in Figure 2, a 9.15 \( M_\odot \) progenitor (Smartt et al. 2009) gives an expected propagation time of \( \lesssim 1 \) day, while for a 27 \( M_\odot \) model (Utrobin & Chugai 2011) this would be \( \sim 1 \) day later.

3. THE HARBINGER

The critical aspect of a triggered search for SBO is the ability to detect that a massive stellar core has collapsed before the SBO photons arrive\(^4\) (with a low rate of false positives) and to notify the astronomical community rapidly. Neutrinos are of particular interest since the data from SN 1987A (Bionta et al. 1987; Hirata et al. 1987) provide the general SN neutrino burst properties. Much of the existing literature on this topic is useful (e.g., Scholberg 2000; Calzavara & Matzner 2004), yet somewhat dated, based on those detectors that were in operation a decade ago. Here we will consider both Galactic and extragalactic events in turn.

3.1. One in Every Crowd: Locating a Galactic SN

The task of identifying the SBO can be simplified to the extent that data from the neutrino harbinger can be quickly analyzed to pinpoint the angular region likely to contain the SN. This is essential in the case of a Galactic event, as otherwise the scanning must encompass all angles. There has been some important work preparing the community for rapid sharing and coordinated analysis of data, with the organization of the Supernova Early Warning System (SNEWS; Antoniouli et al. 2004) being an outstanding example. We first review the conclusions for a Galactic SN, the focus of previous work.

\(^4\) The earliest photons actually arise from heating of the hydrogen envelope by the core \( \bar{v}_e \) burst. However, for a low-mass Fe-core supernova the energy deposition is \( \sim (1–3) \times 10^{52} \text{ ergs} \), depending on assumptions about neutrino temperatures and oscillation effects, far below the SBO energies given above. Specific gamma-ray signals associated with \( \bar{v}_e + p \rightarrow n + e^+ \) and annihilation from \( n + p \rightarrow d + y \) have also been considered, but found to be undetectable with present or envisioned detectors (Lu & Qian 2007).
Studies have focused on two techniques, exploiting the pointing capabilities of an individual water, heavy water, or liquid argon neutrino detector to locate an event, or coordinating the results from several detectors to determine location by timing and triangulation (gravitational waves also rely on triangulation and with multiple detectors, possibly including the use of templates, might achieve a localization comparable to neutrinos for a Galactic SN; e.g., Aasi et al. 2013; Wen & Chen 2010, although our focus shall be on neutrinos). The consensus from past studies has been that the more sensitive technique is pointing (Scholberg 2012).

In a water detector, the limiting factor is the finite angular resolution in reconstructing the neutrino direction via the Cerenkov light from the resulting electron/positron. Despite the much weaker signal for $\nu_e + e^- \rightarrow \nu_e + e^-$ elastic scattering—typically $\sim 1/30$ the SN $\bar{\nu}_e + p \rightarrow n + e^+$ signal, depending on the detector threshold—this is the more effective pointing reaction due to the sharply forward-peaked cross section. (The charged current $\bar{\nu}_e$ reaction in water is approximately flat in angle, requiring an analysis that exploits small, energy-dependent anisotropies in the detected $\bar{\nu}_e$ events.)

Super-Kamiokande will record $\sim 300 \nu_e + e^- \rightarrow \nu_e + e^-$ events from a $\sim 10$ kpc Galactic SN, leading to an excess in the SN direction on top of the nearly isotropic background of $\sim 10^4 \bar{\nu}_e + p \rightarrow n + e^+$ events (Ikeda et al. 2007). Beacom & Vogel (1999) concluded that the localization possible in this case is an angular cone of $\sim 5^\circ$ radius. The Collaboration is considering adding gadolinium to the detector to allow for the detection of neutrons, which are currently invisible in Super-K (Beacom & Vagins 2004). If this is done, the pointing capabilities could be improved by vetoing $\bar{\nu}_e$ events to isolate the otherwise-indistinguishable $e^-$ scattering. The future detector Hyper-Kamiokande (Abe et al. 2011), with a fiducial volume 25 times that of Super-K, could localize a Galactic event to $\sim 1^\circ$.

In their exploration of the potential of timing and triangulation, Beacom & Vogel (1999) exploited the $\tau \sim 30$ ms rise

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**Figure 3.** Probability of a core-collapse originating at an unknown distance based only on a given number of neutrino events detected in 560 kton (dashed) and 5 Mton water Cherenkov detectors (solid; as numbered). Also shown are the supernova rates for galaxies used in our estimate of the local rate, shown as circles (with area proportion to the rate) at the distance of each galaxy (note that these do not factor into the curves displayed, but are reflected in Table 1). (A color version of this figure is available in the online journal.)
time in the neutrino signal, determining that the event could be localized to within a time that scaled as $\tau/\sqrt{N}$, where $N$ is the number of detected events. Their conclusion, that triangulation was a factor of $\sim 100$ less effective in limiting $\delta(\cos \theta)$, when compared to pointing by elastic scattering, was based on a comparison of the Super-Kamiokande and SNO detectors, and thus was limited by the smaller detector. It is possible that this is too pessimistic, however, as there may be other, more distinctive time variations in the SN neutrino flux.

Recent studies have seen high-frequency (10–200 Hz) stochastic variations in two-dimensional and three-dimensional simulations of the SN flux—a consequence of convective instabilities and the standing accretion shock instability—and concluded that these variations would currently be detectable in IceCube for an SN within $\sim 2–10$ kpc, depending on assumptions, despite a very limiting signal-to-noise ratio in that detector of $\sim 1/10$ (Lund et al. 2012; Brandt et al. 2011; Tamborra et al. 2013). The SN neutrino event rate in Hyper-Kamiokande during the first several seconds of the burst should be $\sim 50/\text{ms}$, about $1/3$ the rate in IceCube, but with negligible background. Thus, once more than one detector of this class is operational, it is possible that timing via detailed pattern matching would greatly increase the power of this technique.

3.2. SNe in the Local Universe

While future neutrino advances will localize a Galactic SN to within a degree, it will not solve the problem that motivates this study, the $\sim 100$ yr wait between events. Further, whenever the next Galactic SN does occur, it will still only represent one class of the great variety of SNe. Unfortunately, neither of the techniques described above can be applied successfully to the extragalactic SNe of interest here, as both depend fundamentally on large statistics.

The prospect of detecting an SN core collapse from far beyond the Galaxy long appeared to be impractical. However, in Ando et al. (2005) it was recognized that a 1 Mton detector would expect $\sim 1 \bar{\nu}_e + p \rightarrow n + e^+$ event from out to a few Mpc, which could be searched for after an optical discovery. An SN in Andromeda, which is also an infrequent source of SNe, would produce $\sim 40$ events in Hyper-Kamiokande. If we set as our goal reaching starburst galaxies such as M82 and IC 342, where SNe are far more frequent (see Figures 1 and 3), then the best we can hope to achieve is a signal distinguishable from background. As these starburst galaxies are at distances of over $3$ Mpc, each core collapse would produce $\sim 10$ counts/event in a 5 Mton detector and $\sim 2–3$ in Hyper-Kamiokande.

We emphasize that, for the purpose of triggering, an independent detection of the core collapse is essential. Following the methods in Kistler et al. (2011), we address the prospects for detecting “mini-bursts” of core-collapse neutrino events. For a 5 Mton detector, background rates dictate that $\geq 3$ SN $\bar{\nu}_e$ events are required to reduce false triggers. In a 560 kton detector, such as Hyper-Kamiokande, the absolute background rate is lower and adding gadolinium should allow a reduction to $\geq 2$ events, with a lower energy threshold (we use $E_{\bar{\nu}_e} \gtrsim 16$ MeV). In Figure 1, we indicate nominal detector reaches by the distances at which $90\%$ or $10\%$ of SNe are detectable for these thresholds (complete probability curves are available in Kistler et al. 2011 and Ando et al. 2005).

To estimate the nearby rate of burst detections, we use SN rates derived from two techniques. We consider $B$-band emission, using the updated empirical conversion factors from Li et al. (2011), from the 451 galaxies in the Karachentsev et al. (2004) catalog, as well as the $B$-band and UV-based rates (rather than $H_{\alpha}$; see Botticella et al. 2012) from the 315 galaxies in Lee et al. (2009) assuming a minimum SN mass of $8 M_\odot$. To reach the greater completeness needed for neutrino burst association, we merge the two catalogs, using the average of the $B$-band and UV rate for galaxies appearing in both, for a total of 589 galaxies within $\sim 11$ Mpc (see Figure 3).

In Figure 1, we see that the galaxy catalog rate falls below the observations of nearby SNe. As in Kistler et al. (2011), we assume a generic Fermi–Dirac SN $\bar{\nu}_e$ spectrum with an average energy of 15 MeV yielding a total energy of $5 \times 10^{52}$ erg. Using the catalog (excluding the Milky Way) and the observed SNe as lower and upper bounds, we find expected decadal core-collapse detection rates of $\sim 4–8$ in 5 Mton and $\sim 1–2$ in 560 kton fiducial volumes. Both are well above current capabilities, set by the Galactic rate of one per 30–100 yr.

The number of potential SN host galaxies within neutrino range of Earth is finite, but if the only information available is that a neutrino burst has been detected, all would need to be scanned to find the SBO. Here we argue that the specific details of the neutrino burst (the number of counts, and possibly the hardness of the neutrino spectrum) and the size of the source (e.g., M82 has an angular size of less than $0.5$) will allow one to focus telescope time on a subset of candidate galaxies that reside at an appropriate distance from Earth.

We next examine the quantitative prospects for deriving a distance to the core collapse from neutrinos alone. Figure 3 displays the probability of an SN arising from an unknown distance given only the number of $\bar{\nu}_e$ events seen in a 560 kton or 5 Mton detector (assuming our fiducial $\bar{\nu}_e$ spectrum, an input that we expect future simulations will further refine). Even for low event counts, this narrows the range of distances that needs to be considered, so that an SBO search can be confined roughly to a shell of neighboring galaxies.

Variations in $\bar{\nu}_e$ production because of variations in the progenitor can be estimated from the library of progenitors recently generated by Nakazato et al. (2013). Detection rates in water Cherenkov detectors are approximately proportional to the number of $\bar{\nu}_e$ emitted times $(E_{\bar{\nu}_e})^2$ (due to the energy dependence of the inverse-beta cross section). Forming this figure of merit from the various metallicity $Z = 0.02$ progenitors in Table 1 of Nakazato et al. (2013) and demanding that our associated uncertainty encompasses the full range, we find that event rates can vary by $\pm 42\%$ (although one should account for a declining stellar initial mass function). The Poisson uncertainty on the distance inherent in Figure 3 should tend to be more important for small numbers of counts. The effects of neutrino oscillations have also been evaluated recently in connection with the diffuse supernova neutrino background (Lunardini & Tamborra 2012) and shown to be relatively modest.

Taking into account both the probabilities and SN rates shown in Figure 3, we determine the overall probability, $P_n$, for an SN to have arisen in each galaxy in our set given an observed number of neutrino counts, $n$, in a 560 kton or 5 Mton detector. In Table 1, we rank these to show the most likely locations for some of the most likely $\bar{\nu}_e$ event counts. Although we consider 589 galaxies, we see that strongly star-forming galaxies are the most probable and limited in number. Figure 4 displays how larger event counts limit the number of galaxies required to reach a given probability when using this set.

This strategy for limiting the SBO search is compatible with the anticipated meager number of events that will be
Kamikande should be able to make a quick determination of the range of likely distances to the progenitor, thereby informing SBO searches.

4. THE CHASE

Along with the shock propagation time, the duration of the SBO event determines the requirements for a triggered search. This is set by a combination of the photon diffusion time, $t_d\sim r_s/c$. Following Calzavara & Matzner (2004), we set $t_d = l_s/v_s$ based on the point where $t_{\text{shock}} = c/v_s = t_s = \frac{\int_{\rho} dr \rho}{\kappa v_s}$, with $\kappa = 0.34 \text{ cm}^2 \text{ g}^{-1}$, to find $t \sim (t_s^2 + t_d^2)^{1/2}$. The results for the progenitor models are shown in Figure 2. For a fixed stellar mass/radius, the polytropic solutions tend to yield somewhat longer $t_d$ values, although this depends on the details of the outer density profile at the time of explosion and should thus be accounted for in future modeling.

Ideally one would like to accurately determine both the duration of the SBO and the time of SBO relative to a harbinger of core collapse. These two times are in fact correlated, though they differ in their detailed dependences on progenitor properties and thus provide independent constraints on the stellar models that would be employed to interpret an SN event. The clustering of the progenitor types—three islands corresponding to W-R, BSG, and RSG stars appear in Figure 2—shows that the requirements for a successful “chase” depend greatly on the progenitor.

Although there are variations even within each class, local SBO signals are expected to be quite bright. Estimating the luminosity using Equation (1) for BSG (or $E_{\nu}$ for $n = 3/2$ from Matzner & McKee 1999 for RSG) along with the above durations yields ranges of $\sim(1-5) \times 10^{44} \text{ erg s}^{-1}$ for RSG and $\sim(3-10) \times 10^{44} \text{ erg s}^{-1}$ for BSG, which is $\gtrsim 10^{51} L_\odot$ for even the least luminous. Assuming a distance of 5 Mpc leads to energy fluxes in the range $10^{-7} - 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$, with RSG temperatures of $\sim(3-6) \times 10^5 \text{ K}$ and $\sim(1-3) \times 10^6 \text{ K}$ for BSG.

To determine the shock propagation time (or to have a reasonable probability of doing so), scans must be done on times at least comparable to the much shorter SBO duration. If the SBO is identified, the determination of the light curve can proceed. Observations now imply that RSGs are the typical progenitors of Type II-P SNe, which constitute three out of five core-collapse SNe (Smartt et al. 2009). RSGs are also the best candidates for successful observation of both SBO arrival time and duration, with the available $10^3 - 10^4 \text{ s}$ possibly allowing multiple observations of each candidate galaxy following the neutrino alert.

The likelihood of SBO observation can be increased by combining data from the neutrino burst with information on likely sources within our neighborhood, such as that given in Table 1. In this way telescope time could be allocated to the most likely host galaxies, in proportion to the expectations that these

Table 1

| $P_{\nu_\mu}$ (560 kton) | $P_{\nu_\tau}$ (560 kton) | $P_{\nu_\mu}$ (5 Mton) | $P_{\nu_\tau}$ (5 Mton) | $P_{\nu_\mu}$ (5 Mton) | $P_{\nu_\tau}$ (5 Mton) |
|-------------------------|--------------------------|-----------------------|------------------------|-----------------------|------------------------|
| IC 342 (0.220)          | IC 342 (0.258)           | NGC 6946 (0.093)      | NGC 253 (0.11)         | IC 342 (0.218)         | IC 342 (0.333)         |
| NGC 253 (0.078)         | Maffei 2 (0.087)         | NGC 253 (0.063)       | M83 (0.086)            | NGC 253 (0.134)        | M82 (0.091)            |
| M82 (0.063)             | M82 (0.059)              | M83 (0.062)           | IC 342 (0.076)         | M82 (0.093)            | NGC 253 (0.084)        |
| Maffei 2 (0.058)         | NGC 253 (0.059)          | M101 (0.054)          | NGC 6946 (0.075)       | NGC 4945 (0.087)       | NGC 4945 (0.078)       |
| NGC 4945 (0.056)        | NGC 4945 (0.052)         | M51 (0.037)           | NGC 4945 (0.052)       | M83 (0.061)            | Maffei 2 (0.065)        |

Figure 4. Cumulative probability vs. number of galaxies, with curves corresponding to 560 kton (dashed) and 5 Mton detectors (solid) as in Figure 3. (A color version of this figure is available in the online journal.)

detected from an extragalactic SN. For example, the detection of 20 events would determine the flux to $\sim 22\%$, well below the 42\% theoretical flux uncertainty we associated with the unknown properties of the SN progenitor. A more significant difference could arise if collapse proceeds to a black hole and a hard spectrum difference could arise if collapse proceeds to a black hole and a hard spectrum. If this fraction is not to be substantial, the fraction of cores collapses that end in black holes should be inferred from the progenitor models shown in Figure 2. For a fixed stellar mass/radius, the polytropic solutions tend to yield somewhat longer $t_d$ values, although this depends on the details of the outer density profile at the time of explosion and should thus be accounted for in future modeling.

It was not until the late 1980s that the idea of the analysis was so simple that a collaboration like Hyper-Kamiokande should be able to make a quick determination of the range of likely distances to the progenitor, thereby informing SBO searches.
galaxies might host detectable events. In principle, neutrino detection could provide directional information on the host, depending on the number of events detected (as discussed earlier).

A model for the distribution of core-collapse notices, and general requirements of a telescope useful for SBO searches, can be taken from the remarkably successful Swift satellite (Gehrels et al. 2004; Kanner et al. 2012). Upon detection, information will have to be quickly disseminated so that predefined searches can be initiated. Instruments such as Swift, with the ability to rapidly slew and observe simultaneously in both the near-UV and soft X-ray, would be invaluable to observe the spectral peak. For instance, the SBO from the Type Ib SN 2008D was clearly seen by the Swift X-ray Telescope from a distance of 27 Mpc (Soderberg et al. 2008). However, the short propagation times and durations for compact BSG/W-R progenitors will likely necessitate an alternative to repeated pointing and slewing of an entire space telescope due to the requisite higher cadence of observations.

One way to get around this constraint would be to utilize wide-field instruments. A soft X-ray mission (e.g., Gehrels et al. 2012; Osborne et al. 2013) could achieve a sensitivity to SBO events from distances much larger than the $\lesssim 10$ Mpc scale of interest for neutrinos (see Calzavara & Matzner 2004 for detailed prospects). A system of UV space telescopes aiming to reach SBO up to $\gtrsim 100$ Mpc is discussed by Sagiv et al. (2013; see their Figure 2). There also exist conceptual studies of rapidly slewing space-bound telescopes that could achieve response times 30–100 times shorter than Swift, potentially to $1$ s, over substantial ($\gtrsim 35$') fields of view (Jeong et al. 2013).

Another possibility is to instead try to catch the longer-wavelength tail. Adams et al. (2013) discuss a dedicated system that requires only small, ground-based telescopes, estimating that upward of 35% of BSG events could be detected at a modest cost in a blind search. Optimizing such a survey instead for RSG can yield close to three out of four such events. Additionally, the calculations of Lovegrove & Woosley (2013) and Piro (2013) indicate that if core collapse proceeds to a black hole, long, relatively cool optical transients may follow. Piro (2013) suggests a $\sim 10^4$ K SBO lasting from 3 to 10 days, thus amenable to such ground-based searches.

A coordination of observational techniques is needed to handle the wide variety of environments that an SN can occur within. For example, our galaxy sample indicates that NGC 253 and M82 are among the most likely SN hosts, yet both have highly extincted starburst regions. The effects of intervening absorption will vary depending on the band observed (see, e.g., Calzavara & Matzner 2004). Additionally, it should be determined in advance what each instrument that will be available can contribute to such searches. For instance, although a single slewing space telescope might not feasibly conduct a comprehensive survey for short-duration events alone, it would not occupy much time to observe one or a few of the most likely host galaxies guided by the neutrino count data. Such an approach must also account for the time evolution of the SBO spectrum due to cooling (as illustrated in Figure 1 of Sagiv et al. 2013). Ideally, the process of partitioning search strategies would be automated.

5. THE AFTERMATH

Knowing that the SBO is on the way would also allow for rapid observations of the ensuing optical SN, so that these measurements can be made at the earliest possible times (e.g., Stritzinger et al. 2002; Quimby et al. 2007; Ofek et al. 2010). This will be useful for studying the SN and the star, e.g., by inferring the energy imparted by the shock (Arnett 1996). If no SBO is found, prompt observation of the SN would be important as a bound on the shock propagation time, which then could lead to an estimate of the probability that the SBO was missed, using qualitative correlations such as those in Figure 2.

Observations of the SN progenitor by surveys of supergiants in the local universe (e.g., Kochanek et al. 2008) would imply a stellar mass, although models are needed to interpret such data. Thus, the direct determinations of stellar properties afforded by SBO measurements will be valuable. This is particularly true for cases where progenitor information is ambiguous due to a nearby cluster or binary companion. One can even imagine taking images during the period between the neutrino warning and the SBO to compare with earlier epochs.

The primary objective discussed here is based on measuring the times of both core collapse and shock emergence. If surveys are conducted to observe SBO events without a trigger, it is worth considering what neutrino signals would be useful if detection is not independently possible, i.e., looking after the fact for fewer counts than the two for Hyper-Kamiokande or three for 5 Mton used above. For a Hyper-K size detector, Ando et al. (2005) determined that searching for even single events from the period preceding an SN could be feasible, depending on the expected background in the time window that must be considered. Comparing to Figure 2, for SN Ibc or BSG events, this would be rather short if the SBO is detected and, since the neutrino burst is much briefer, one neutrino event would be sufficient to time the shock passage. For RSG, comparing the propagation time differences in Figure 2 between adjacent progenitor masses, even while keeping energy injection fixed, the CC–SBO delay is most likely $\sim$ days. One might try to further model the SBO and attempt to deduce the core-collapse timing, although this is what one would like to test.

Using the rate given in Kistler et al. (2011), in a 5 Mton detector the single event background is $\sim 2 \text{ hour}^{-1}$, complicating the interpretation of a lone detected event for even BSG progenitors. However, the rate of random double coincidences (within 10 s) is $\sim 0.2 \text{ day}^{-1}$, which, while being too high to allow independent triggers, could be low enough for searches of data taken prior to even RSG SBO events. Using the same core-collapse rate estimators as before, this would add $\sim 2$–4 events per decade. This assumes the detector discussed in Kistler et al. (2011). A multi-megaton detector that utilizes similar detection principles as IceCube, but with much denser instrumentation to reach a $\sim 10$ MeV threshold and situated deep within IceCube to use the outer detector as a muon veto, has also been put forward (IceCube Collaboration 2011). A study of potential designs indicates that an effective detector mass upward of $\sim 7.5$ Mton could be reached if photomultiplier tube noise can be sufficiently reduced (Boser et al. 2013), the feasibility of which is being investigated (Schulte et al. 2013). The count thresholds for this technique will need to be determined for each design, but aim to achieve detection rates comparable to those presented above.

6. DISCUSSION AND CONCLUSIONS

The possibility of unifying a variety of observational techniques to study the complete chain of events following a core collapse is a difficult, yet compelling, challenge. Neutrino and gravitational wave telescopes monitoring the cores of massive stars for signs of collapse can supply advanced notice that a shock should have just formed and is on its way to the star’s
surface. Neutrinos are promising because (1) from SN 1987A, we understand what to look for, and (2) neutrino telescopes can be scaled to continuously cover out to several Mpc. This will allow concerted searches for the SBO, which, despite being thought to be ubiquitous in core-collapse SNe, perhaps even for those forming black holes often considered as failures, is one of the rarest observed astronomical events due to its transient nature and otherwise unpredictable appearance.

We can extract physics from the SBO only if we identify the photons from the collapsed star before they pass us by. For a Galactic SN, Super-Kamiokande (Ikeda et al. 2007) and IceCube (Abbasi et al. 2011) can currently alert us to the event, nature and otherwise unpredictable appearance. Those forming black holes often considered as failures, is one thought to be ubiquitous in core-collapse SNe, perhaps even for will allow concerted searches for the SBO, which, despite being provided by NASA through the Einstein Fellowship Program, grant PF0-110074, W.C.H. by the US DOE under contracts DE-SC00046548 (UC Berkeley) and DE-AC02-98CH10886 (LBNL) and by the Alexander von Humboldt Foundation, and H.Y. by the LANL LDRD program.

We thank Baha Balantekin, John Beacom, Boris Kayser, Chris Kochanek, Chris Matzner, Chris McKee, Casey Meakin, Kate Scholberg, Kris Stanek, Todd Thompson, Terry Walker, and Lincoln Wolfenstein for discussions. M.D.K. acknowledges support provided by NASA through the Einstein Fellowship Program, grant PF0-110074, W.C.H. by the US DOE under contracts DE-SC00046548 (UC Berkeley) and DE-AC02-98CH10886 (LBNL) and by the Alexander von Humboldt Foundation, and H.Y. by the LANL LDRD program.

Modern gamma-ray burst searches with Swift provides a model for how this can be done and illustrates how a field can be transformed with rapid follow-up observations.

The identification of SBO events will likely prove to be a powerful tool for determining properties of the progenitors and thus correlating progenitor properties with other observables, optical, neutrino, and gravitational. This progenitor specificity will establish a tighter connection between observation and modeling, providing a better test of our understanding of the supernova mechanism.
