PHYSICAL REVIEW D **84,** 063002 (2011)

Revealing local failed supernovae with neutrino telescopes

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(Received 1 April 2011; published 1 September 2011)

We study the detectability of neutrino bursts from nearby direct black hole-forming collapses (failed supernovae) at Megaton (Mt) detectors. Because of their high energetics, these bursts could be identified—by the time coincidence of $N \geq 2$ or $N \geq 3$ events within a $\sim$1 s time window—from as far as $\sim$4–5 Mpc away. This distance encloses several supernova-rich galaxies, so that failed supernova bursts could be detected at a rate of up to one per decade, comparable to the expected rate of the more common, but less energetic, neutron star-forming collapses. Thus, the detection of a failed supernova within the lifetime of a Mt detector is realistic. It might give the first evidence of direct black hole formation, with important implications on the physics of this phenomenon.

DOI: 10.1103/PhysRevD.84.063002 PACS numbers: 97.60.Bw, 14.60.Pq

The gravitational collapse of a stellar core is one of the most extreme phenomena in our universe. There, matter is pushed to its limits of density, and most of the energy is emitted by a nonelectromagnetic form of radiation, the neutrinos, rather than in the final explosion (supernova) that often follows the collapse.

Neutrinos are true tracers of core collapse. Because of their long mean free path, they give a direct image of the outskirts of the collapsed core. Furthermore, they are the only emission—together with gravitational waves—that always accompanies a collapse. Indeed, it is predicted that 10–20% of collapses directly generate a black hole [1], with a brief and strong phase of neutrino emission, and no explosion [2–4]. For these *failed supernovae*, the star simply disappears from the sky, leaving the neutrino burst as a unique messenger of the event.

At present, the detection of supernova neutrino bursts is still limited by long waiting times, as current detectors—of $\mathcal{O}(10)$ kt mass—can only capture the 1–3 bursts per century in our galactic neighborhood [5–7]. Upcoming Mt scale detectors will start to overcome the time barrier: for the common, neutron star-forming collapses (which have an accompanying explosion), they have a volume of sensitivity of 1–2 Mpc radius [6], ($1\ Mpc = 3.086 \times 10^{22}\ m$), where about $\sim$1 collapse per decade is predicted [6]. By applying a 10–20% fraction, this translates into about 1–2 detections of failed supernova bursts per century, still discouraging for an experiment lifetime of a few decades.

In fact, however, certain factors enhance the detectability of neutrino bursts from failed supernovae. First, the higher neutrino luminosity and average energy of failed supernovae correspond to a larger distance of sensitivity, a distance that happens—as will be seen here—to be just enough to bring within the range of observability several major, supernova-rich galaxies located 3–4 Mpc away. This fortunate circumstance can boost the expected detection rate significantly, similarly to what was discussed for the diffuse supernova neutrino flux [8]. Furthermore, the shorter duration of a failed supernova burst (0.5–1 s) makes it easier to identify: the time coincidence of two neutrino events within $\sim$1 s or so might be sufficient for discrimination against background.

The fact that detecting individual neutrino bursts from failed supernovae is realistic, with a Mt detector, implies the potential to reveal—possibly for the first time—the direct collapse of a star into a black hole, with several implications on the physics of this transition, such as the rate of accretion of matter on the collapsed core, the equation of state of nuclear matter, etc. Here, we elaborate on the idea of the enhanced detection rate of failed supernova bursts, and discuss its implications.

Failed supernovae (or direct black hole-forming collapses, DBHFCs) are predicted to originate from stars with mass above $M_{\rm min} \sim 25$–$40 M_\odot$ (with $M_\odot$ the mass of the Sun) [1,2], corresponding to 9–22% of all collapsing stars (see, e.g., [8]). Numerical simulations [3,4,9–12] indicate that their neutrino burst lasts $\sim$1 s or less, and has up to $L \sim 5 \times 10^{53}$ ergs luminosity, due to the rapid contraction of the newly formed protoneutron star preceding the black hole formation. The produced electron neutrinos and antineutrinos, ν_e and $\bar{\nu}_e$, have especially high luminosity, $L_{0e} \simeq L_{0\bar{e}} \sim 10^{53}$ ergs, due to the high rate of electron and positron captures on nuclei. Their average energy can reach $E_{0e} \simeq E_{0\bar{e}} \sim 20$–$24$ MeV.

Because of oscillations in the star, the $\bar{\nu}_e$ flux in a detector is an admixture of the unoscillated flavor fluxes: $F_{\bar{e}} = \bar{p} F^0_{\bar{e}} + (1 - \bar{p}) F^0_x$, where x indicates the non-electron species, $\nu_x = \nu_\mu$, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$, and $\bar{p}$ is the $\bar{\nu}_e$ survival probability [13]. Following [8,12,14], we consider $\bar{p} = 0$–0.68 and give results for the energy-independent, limiting case of $\bar{p} = 0.68$, unless otherwise specified. We take the neutrino fluxes from Fig. 5 of [12,32], for the Shen *et al.* equation of state of nuclear matter. This set of flux and oscillation parameters maximizes $F_{\bar{e}}$ [12], and so it is adequate to estimate the maximum potential of detection of failed supernovae.

For comparison, we also consider bursts from neutron star-forming collapses (NSFCs). These last 10–20 s and have typical parameters $L \sim 3 \times 10^{53}$ ergs, $L_{0\bar{e}} \sim L_{0x} \sim 0.5 \times 10^{53}$ ergs, $E_{0\bar{e}} \sim 15$ MeV, and $E_{0x} \sim 18$ MeV. The spectra of the produced neutrinos in each flavor typically have the form of a power-law times an exponential [15]. We restrict to the case in which $\bar{p}$ has the same value for the two collapse types [12,14].

Let us consider the response of a 1 Mt water Cherenkov detector [16–18] to a neutrino burst. The dominant detection reaction is inverse beta decay, $\bar{\nu}_e + p \rightarrow n + e^+$, which we model as in [19]. The expected positron spectra for the two collapse types are shown in Fig. 1. The higher energetics of a failed supernova is evident in the figure.

An experiment looks for inverse beta decay events within fixed time and energy windows designed to maximize the signal to background ratio [20]. Typical time windows could be $\Delta t = 10$ s and $\Delta t = 1$ s for neutron star-forming collapses and failed supernovae [21]. The energy windows are limited by the background at low energy; a threshold of about 16 MeV in positron energy seems realistic [20]. The windows could be defined as including at least 80% of the events above this threshold: we find the intervals $E_e = 16$–33 MeV and $E_e = 16$–56 MeV for NSFCs and DBHFCs, respectively. A neutrino burst is identified ("detected") if $N \geq N_{\min} \sim 2$–3 events are observed in the energy window with time separation less than Δt. Note that the number of events due to a failed supernova increases with increasing $\bar{p}$ (Fig. 1), i.e., with larger survival of the more luminous original $\bar{\nu}_e$ component. It can be as large as $\mu(D) \simeq 64(1\ \mathrm{Mpc}/D)^2$, up to 5 times larger than that from a NSFC. Therefore, 2 (3) events are expected from a failed supernova as far as $D \sim 6$ Mpc ($D \sim 5$ Mpc).

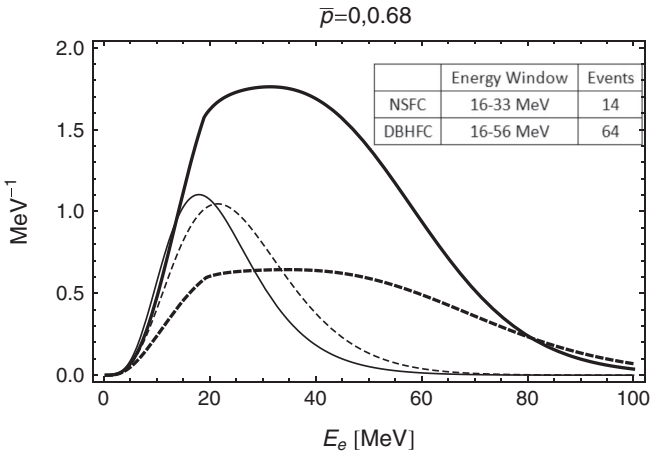

FIG. 1. Positron energy spectra at a 1 Mt water Cherenkov detector from a neutron star-forming collapse (thin curves) and a black hole-forming collapse (failed supernova, thick curves), at distance $D = 1$ Mpc. Dashed curves: $\bar{p} = 0$; solid: $\bar{p} = 0.68$. The Shen *et al.* equation of state is used for the failed supernova [12]. Integrated numbers of events are also given for $\bar{p} = 0.68$ and realistic energy windows of detection (see text).

Given the "true" number of events, μ, the probability of detection of a burst (i.e., $N \geq N_{\min}$ positrons observed) in the detector is given by the Poisson distribution:

$$P(N_{\min}, D) = \sum_{n=N_{\min}}^{\infty} \frac{\mu^n(D)}{n!} e^{-\mu(D)} \tag{1}$$

[7]. It is shown in Fig. 2(a) as a function of the distance D for $N_{\min} = 2$, 3. The figure confirms the expectation of a larger range of sensitivity to failed supernovae, with a probability of detection as large as 0.8 for $D = D_s \simeq$ 4–4.5 Mpc, which can be thus considered a typical distance of sensitivity. The corresponding distance for a neutron star-forming collapse is $D_s \simeq 2$–2.5 Mpc.

We now come to the key point of this work: how the increased distance of sensitivity allows to probe a region of high core collapse rate. Figure 2(b) gives the nearby rates

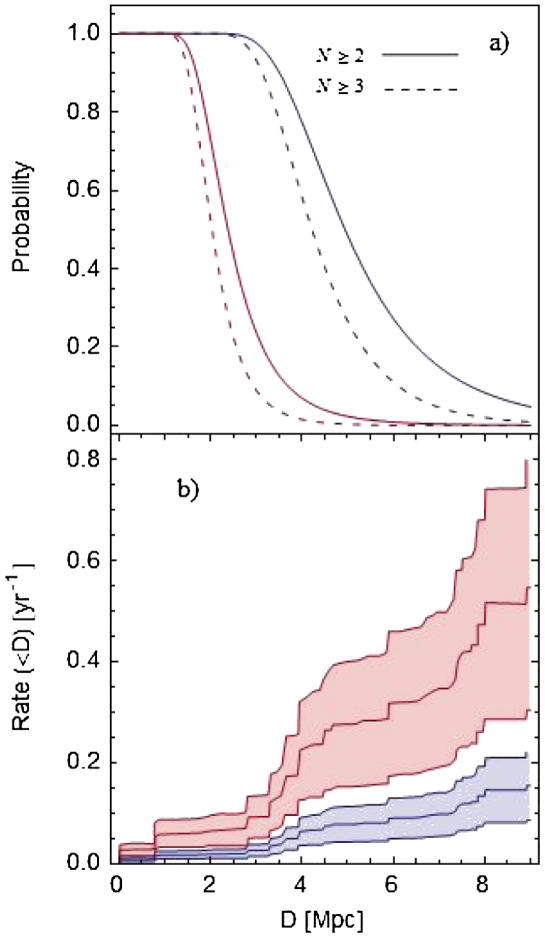

FIG. 2 (color online). (a) The Poissonian probabilities to detect $N \geq 2$ and $N \geq 3$ events at a 1 Mt water Cherenkov detector for neutron star-forming collapses (lower curves, red) and black hole-forming collapses (upper curves, blue). The results of Fig. 1 with $\bar{p} = 0.68$ are used. (b) the rates of the two collapse types within a radius D from Earth, with their uncertainties. The lower shaded region refers to failed supernovae. These rates are taken from [6] with a fraction $f_{\mathrm{BH}} = 0.22$ of failed supernovae.

of the two types of collapses, $R_{\rm BH}$ and $R_{\rm NS}$, within a distance D, with their uncertainty. They are derived from the collapse rate in [6] (which is obtained from a catalog of galaxies [22] with conversion factors between luminosities and core collapse rates [23]), under the assumption of a constant, distance-independent, ratio $f_{\rm BH} = 0.22$ of failed supernovae. (This assumption is necessarily tentative, as no data exist about the distribution of failed supernovae.) These rates are higher than the cosmological average [6], and actual supernova observations favor an even higher rate [7]. Therefore, our results based on Fig. 2(b) are conservative.

Figure 2(b) clearly shows the rapid increase of the rates between 3 and 4 Mpc, due to the presence of several galaxies (mainly IC 342, NGC 2403, M 81, M 82, and NGC 4945 [6]), in this interval of distance. This is well within the range of sensitivity for failed supernovae, but only marginally accessible for the less luminous NSFCs. Within the typical distance of sensitivity, D_s, Fig. 2(b) gives a rate of $\sim$0.04–0.10 yr^{-1} for failed supernovae, and $\sim$0.07–0.14 yr^{-1} for neutron star-forming collapses. The two rates are comparable, showing that the increased distance of sensitivity for failed supernovae compensates in part for their rarity.

One can calculate the expected rate of detections of bursts from DBHFCs within a distance D [7]:

$$R^{\rm det}_{\rm BH}(N_{\rm min}, D) = \sum_{i, D_i \le D} \Delta R_{{\rm BH},i} P(N_{\rm min}, D_i). \qquad (2)$$

The sum is over bins of distance, with $D_i \le D$, and $\Delta R_{{\rm BH},i}$ is the failed supernova rate in each bin, so that $\sum_{i,D_i \le D} \Delta R_{{\rm BH},i} = R_{\rm BH}(D)$. An expression analogous to Eq. (2) holds for the rate of detections of NSFCs, $R^{\rm det}_{\rm NS}$.

Figure 3 gives $R^{\rm det}_{\rm BH}$ and $R^{\rm det}_{\rm NS}$ as functions of the distance. Naturally, for each supernova type, the detection rate follows the collapse rate for $D \ll D_s$; it then flattens for larger distances, reflecting the suppression due to the small detection probability [Fig. 2(a)]. This flattening occurs around 4 Mpc for NSFCs, and at $\sim$8–9 Mpc for DBHFCs. Depending on the normalization of the collapse rate, the detection rates for the two collapse types reach $R^{\rm det}_{\rm NS} \sim 0.05$–$0.13$ yr^{-1} and $R^{\rm det}_{\rm BH} \sim 0.04$–$0.11$ yr^{-1}.

Thus, failed supernovae have a chance to be detected within the lifetime of an experiment. Because of their contribution, the total rate of burst detections could be twice as large as previously estimated, with a maximum of about 2 detections per decade.

Typically, expected detection rates are considered promising if they exceed the corresponding background rates, so that an observed burst can be attributed to a supernova with substantial likelihood. Assuming that correlated events can be identified and subtracted [20], the background is given by accidental coincidences of uncorrelated events within the energy and time windows. By rescaling the Super-Kamiokande measurements [25,26] to a Mt mass, we find the rates of uncorrelated events to be $\lambda = 1855$ yr^{-1}

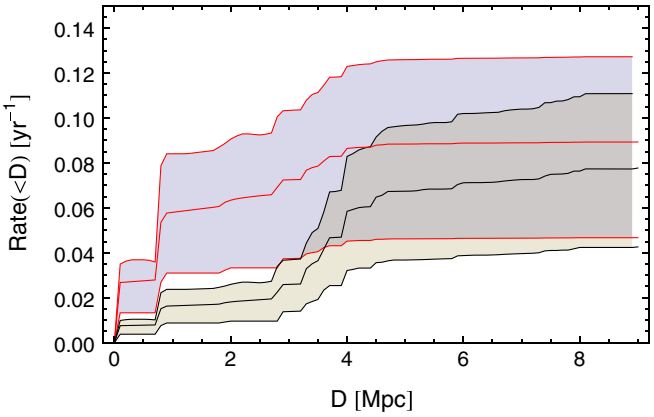

FIG. 3 (color online). The expected rates of detections of neutrino bursts that originate within a radius D from Earth, as functions of D, for neutron star-forming and black hole-forming collapses (upper and lower shaded regions). All parameters are as in Fig. 2 for the case $N \ge 2$.

($\lambda = 680$ yr^{-1}) in the energy window for DBHFCs (NSFCs).

The rate of coincidence of two (three) such uncorrelated events in the time window is (for $\lambda \Delta t \ll 1$) $\omega_2 \simeq \lambda^2 \Delta t$ ($\omega_3 \simeq \lambda^3 \Delta t^2$) [27]. For failed supernovae ($\Delta t = 1$ s), we find $\omega_2 \simeq 0.10$ yr^{-1} and $\omega_3 \simeq 6.4 \times 10^{-6}$ yr^{-1}. The same quantities for the NSFCs time window are $\omega_2 \simeq 0.15$ yr^{-1} and $\omega_3 \simeq 3.1 \times 10^{-5}$ yr^{-1}. For both collapse types, the background doublet rate is comparable to or only slightly higher than the burst rate, so two observed positron events might be sufficient to claim a supernova detection, depending on the details of the experimental setup, and three events should give practically certain identification. For a neutron star-forming collapse, the identification will probably be confirmed by the observation at telescopes of the supernova explosion, unless obscuration is substantial. For failed supernovae, one would have to rely entirely on neutrinos, or, possibly, on the coincident detection of gravitational waves, or on establishing the disappearance of the star [28].

Let us discuss how our results vary with the parameters. Rates depend on $f_{\rm BH}$ as $R^{\rm det}_{\rm BH} \propto f_{\rm BH}$ and $R^{\rm det}_{\rm NS} \propto (1 - f_{\rm BH})$, so rescaling is immediate. The dependences on $\bar{p}$ and on the detector's mass, M, are described in Fig. 4, which gives $R^{\rm det}_{\rm BH}$ within a 10 Mpc radius as a function of M, for different values of $\bar{p}$ and for the central curves in Fig. 2(b). For comparison, the background rates are shown; they depend on the mass as $\omega_2 \propto \lambda^2 \propto M^2$ and $\omega_3 \propto \lambda^3 \propto M^3$. Expectedly, $R^{\rm det}_{\rm BH}$ increases with M and with $\bar{p}$, due to the increase of the number of events (Fig. 1) and therefore of the distance of sensitivity. Beyond $\sim$1 Mt of mass, $\omega_2 > R^{\rm det}_{\rm BH}$, so at least three events will probably be needed to establish detection. For a 5 Mt detector like the proposed TITAND [29], we get $R^{\rm BH}_{\rm det} \simeq 0.10$–$0.16$ yr^{-1} for $N_{\rm min} = 3$.

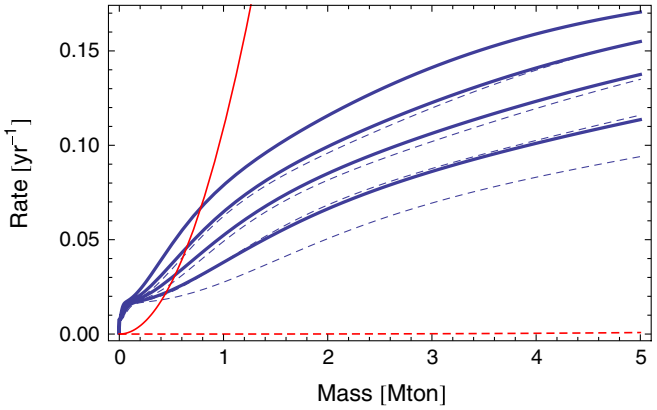

FIG. 4 (color online). Solid lines: rates of background, ω (thin, shown in red online), and of detected failed supernova bursts, $R_{\rm BH}^{\rm det}$ (thin, shown in blue online), for sources within 10 Mpc distance, as a function of the detector mass, for $N \geq 2$ and $\bar{p} = 0$, 0.2, 0.4, 0.68 (lower to upper curves). Note that $\omega \gtrsim R_{\rm BH}^{\rm det}$ for $M \gtrsim 0.8$ Mt. Dashed lines: the same results for $N \geq 3$, for which the background rate is negligibly small (horizontal line).

Results also depend on the equation of state (EoS) of nuclear matter. For the softer Lattimer and Swesty EoS, the neutrino output of a failed supernova is somewhat less luminous and energetic, typically with $E_{0\bar{e}} \simeq 20$ MeV and $L_{0e} \simeq 0.5 \times 10^{53}$ ergs [11,12]. This translates into a reduced distance of sensitivity and therefore a lower rate of detections. Using the fluxes in [12], varying over the oscillation parameters and the local supernova rate, with $M = 1$ Mt, $f_{\rm BH} = 0.22$ and $N_{\rm min} = 2$, we find $R_{\rm det}^{\rm BH} \simeq 0.016$–$0.045$ yr^{-1} within a 10 Mpc radius. This is close to $R_{\rm det}^{\rm NS} f_{\rm BH}/(1 - f_{\rm BH})$, as expected if the neutrino fluxes were the same in the two collapse types.

Summarizing, the detection of a failed supernova at Megaton class neutrino detectors might be a realistic possibility, with a rate of detections reaching about one per decade, depending on the parameters. This is comparable to the rate of the more common neutron star-forming collapses, and is due to the larger distance of sensitivity to failed supernovae, that includes several major, supernova-rich, galaxies. The short, $\sim$1 s duration of a failed supernova burst might allow its unambiguous identification already with the coincidence of two inverse beta decay events within this time interval.

Even with low statistics, the detection of a neutrino burst from a direct black hole-forming collapse will have profound implications. It might be the first observation of a different branch or core collapse, confirming its existence, and giving information on the local rate of failed supernovae. This could be especially interesting in connection with the observed rate of bright supernovae being lower than expected [30], thus allowing for a substantial fraction of failed supernovae. It could also give the exciting opportunity to witness the formation of a black hole in real time, marked by the sudden truncation of the neutrino burst [31]. Considering the strong dependence of failed supernova neutrino bursts on the equation of state, conclusions about it might also be possible, with a high rate of DBHFCs bursts favoring a stiffer EoS.

We are grateful to M. Kistler, D. Leonard, and T. Iida for useful exchanges, and acknowledge the support of the NSF under Grant No. PHY-0854827.

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