Neutrinos from Supernovae as a Trigger for Gravitational Wave Search

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Exploiting an improved analysis of the $\bar{\nu}_e$ signal from the explosion of a galactic core collapse supernova, we show that it is possible to identify within about 10 ms the time of the bounce, which is strongly correlated to the time of the maximum amplitude of the gravitational signal. This allows us to precisely identify the gravitational wave burst timing.

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Neutrinos and gravitational waves (GW) are emitted deep inside a supernova (SN) core and reach terrestrial detectors practically unmodified. They are unique probes to obtain information on the still puzzling scenario of supernova explosion, in particular on the multidimensional dynamics of the protoneutron star and on the physics of the postshock region. The neutrino signal has been detected from the core collapse supernova SN 1987A and, despite low statistics and doubt, it can be said that these observations are in overall agreement with the expectations [1,2]. GWs have not been observed directly yet, but detectors of enhanced sensitivity will operate in the forthcoming years. One of their aims is just the search of GW bursts from core collapse SNe.

The expected amplitude of such an impulsive GW signal [3] challenges the sensitivity of the existing detectors [4–6]. Thus, the use of an external trigger could be a very valuable tool for a successful search of GW signals. In fact, the number of accidental coincidences between GW detectors decreases with the size of the search time window. A triggered search in a small time window allows us to lower the event detection threshold reaching a higher detection probability at a fixed false alarm probability [7–9]. Such a trigger can be provided by the SN neutrino detectors, especially in the case of galactic SNe.

In this work, we quantify the potential of this type of trigger, making reference to existing neutrino and GW detectors. We show that it is possible to predict precisely the time window for GW search by analyzing the neutrino signal from a galactic supernova. We argue that the size of this time window can be matched to the duration of the GW signal itself, that is several orders of magnitude smaller than the duration of the neutrino emission.

Time relation between GWs and neutrinos.—GWs can be emitted during the collapse, or during the explosion, of a core collapse SN due to the star's changing mass quadrupole moment. Recent simulations [3,10,11] show that this gravitational signal is emitted when the collapse of the inner core halts, as dictated by the stiffening of the equation of state at nuclear density. The consequent bounce of the outer core is *pressure dominated* without strong influence of the rotation. Therefore, it is possible to define a generic GW waveform which exhibits a positive prebounce rise and a large negative peak, followed by a ring-down; the time of the bounce is strongly correlated to the time of the maximum amplitude of the gravitational signal [12]. The duration of this signal is about 10 ms. Therefore, our goal is to identify the time of the bounce with an error of the same order using the neutrino signal. This is possible because extensive simulation work [13] on core collapse SNe shows that the onset of $\bar{\nu}_e$ luminosity is closely related to the time of the bounce.

Master equation.—Let us consider a gravitational detector and a neutrino detector with clocks synchronized in universal time (UT). We have

$$T_{\mathrm{bounce}} = T_{\mathrm{1st}} - (t_{\mathrm{GW}} + t_{\mathrm{mass}} \pm t_{\mathrm{fly}} + t_{\mathrm{resp}}), \qquad (1)$$

where times in uppercase are absolute times, in UT, whereas times in lowercase are relative intervals of time. T_{bounce} and T_{1st} are the absolute times of the bounce expected in the gravitational detector and of the first neutrino event detected by the neutrino detector, respectively. The time t_{GW} is the mean interval between the starting point of antineutrino luminosity and the bounce of the outer core on the inner core. This is reliably known and ranges within $t_{\mathrm{GW}} = (1.5\text{–}4.5)$ ms [14]. The time t_{mass} is the delay, due to neutrino mass, between the arrival of GW and neutrino signal; however, this is limited by the cosmological bound $\sum_i m_{\nu_i} < 0.7$ eV, that implies $t_{\mathrm{mass}} \sim 0.27(\frac{m_\nu}{0.23\ \mathrm{eV}})^2(\frac{10\ \mathrm{MeV}}{E_\nu})^2(\frac{D}{10\ \mathrm{kpc}})$ ms; thus, t_{mass} appears negligible. The time interval t_{fly} is the time of fly between the two detectors and depends on the SN position in the sky. Finally the non-negative parameter t_{resp} is the difference of time between the first neutrino and the first event detected. In summary, the main terms in Eq. (1) are the fly time t_{fly} and the response time t_{resp}; their quantitative evaluation is discussed later.

By estimating the various terms in the right-hand side of Eq. (1), we will determine the time of the bounce and the error in that prediction. We note that $\delta T_{\rm bounce}$ and $\delta T_{\rm 1st}$ of the detector clocks are lower than μs, so their uncertainties can be neglected for our purposes.

Measuring $t_{\rm fly}$.—The time of fly between a neutrino and a GW detector separated by the distance $\vec{d}$ is $\pm t_{\rm fly} = \vec{d} \cdot \hat{n}$, where $\hat{n}$ is the direction pointing to SN. The error is negligible for an astronomically identified SN. The same is true when we consider the distance between Large Volume Detector (LVD) and Virgo, $d < 1$ ms; in a sense, this is the ideal configuration. But the distances between Super-Kamiokande (SK) or IceCUBE and the GW detectors LIGO or Virgo are such (see Table I) that could imply an error as large as ~60 ms. Thus we consider $\hat{n}$ as a random variable with most probable value $\hat{n}_*$ and find for $\delta t^2_{\rm fly} = \langle t^2_{\rm fly}\rangle - \langle t_{\rm fly}\rangle^2$:

$$\delta t^2_{\rm fly} = [d^2 - (\vec{d}\cdot\hat{n}_*)^2]\frac{\overline{\sin^2\theta}}{2} + (\vec{d}\cdot\hat{n}_*)^2[\overline{\cos^2\theta} - (\overline{\cos\theta})^2], \tag{2}$$

where $\theta = \arccos(\hat{n}\cdot\hat{n}_*)$ is the angle of $\hat{n}$ with the SN direction. The first term typically dominates, giving an error $\delta t_{\rm fly} \sim \delta\theta d$. Thus, to reach $\delta t_{\rm fly} \leq 5$ ms, we need to determine the angle with a precision of 20°.

Tomas *et al.* [15] discussed how to do this using the elastic scattering (ES) events of SK; e.g., consider a SN at 20 kpc. The search of the expected 35 forward ES events [15,16] is simplified by minimizing the number of inverse beta decay events. These could be diminished by 20% tagging the neutron [17] and again by 20%, requiring a visible energy lower than 30 MeV [2,18]. In fact, due to the neutrino in the final state, the ES events have a low average energy of ~15 MeV [2] that means an angular resolution $\delta\theta = 21°$ [19]. By simulating and then fitting the events we estimate the error in the reconstructed direction. The average error on the angle is $5° \pm 4°$; only 60 out of 10 000 simulations had a reconstructed angle larger than 20°, occasionally due to a downward fluctuation of ES events. Thus, even in the absence of an astronomical identification, it should be possible to determine the direction of the SN precisely enough to reduce the error $\delta t_{\rm fly}$ to the desired level. For a closer SN, larger number of ES events and/or better neutron identification, the measurement will be safer. To facilitate the search for the SN direction further, one could restrict the search to the galactic plane.

Measuring $t_{\rm resp}$.—The value of $t_{\rm resp}$ and its uncertainty has to be extracted from the data. If the astrophysical mechanisms of neutrino emission were known precisely, the inference on the response time would be easy. Unfortunately this is not the case at present and we have to take into account the astrophysical uncertainties. Thus we proceed as follows. First, we suppose that the expected flux of $\bar{\nu}_e$ from a standard core collapse SN explosion can be described by a parametrized model. Then, we fit at the same time the astrophysical parameters *and* the response time from the data.

We adopt and develop a model already used for SN 1987A data analysis [20]. This model describes the $\bar{\nu}_e$ luminosity from the instant when the shock wave, originated from the bounce of the outer iron core on the inner core of the star, reaches the neutrino sphere and begins the neutrino emission, until the end of the detectable neutrino signal. The expression of the flux, whose luminosity is depicted in Fig. 1, is

$$\Phi_{\bar{\nu}_e}(t) = f_r(t)\Phi_a(t) + [1 - j_k(t)]\Phi_c(t - \tau_a). \tag{3}$$

Here t is the relative emission time, while Φ_a, Φ_c, and $j_k(t)$ are the accretion flux, the cooling flux, and the function that links the two emission phases, respectively [21]. The expected rise [14] is described introducing

$$f_r(t) = 1 - e^{-t/\tau_r} \tag{4}$$

that improves the existing parametrizations [20,22]. The time scale $\tau_r \sim 50$–150 ms depends strongly [13,23] on the velocity of the shock wave; τ_r is the new, crucial model parameter. The accretion flux Φ_a is generated by the interactions between the neutrons and the positrons above the shock and is described by three parameters: the initial accreting mass (M_a), the time scale of the accretion phase (τ_a), and the initial temperature of the e^+ (T_a). The cooling flux Φ_c coming from the thermal emission of the new born protoneutron star is proportional to the radius of the neutrino sphere (R_c), shows a time scale (τ_c), and an initial temperature of the emitted antineutrinos (T_c). In summary, our parametrization of the $\bar{\nu}_e$ emission model includes seven astrophysical parameters.

In order to construct a Monte Carlo simulation of a future SN event, we adopt the values found from SN 1987A data analysis [20], namely,

TABLE I. Coordinates of three interferometers and three SN neutrino detectors. The distances with SK, LVD, and IceCUBE are denoted by $d^{\rm SK}$, $d^{\rm LVD}$, and $d^{\rm IceCUBE}$, respectively (note that $t_{\rm fly} \leq d$).

	LIGO I	LIGO II	Virgo	LVD	SK	IceCUBE
Φ	30°30″ N	46°27′ N	43°41′ N	42°28′ N	36°14′ N	90° S
λ	90°45′ W	119°25′ W	10°33′ E	13°33′ E	137°11′ E	139°16′ W
$d^{\rm SK}$	32.1 ms	24.9 ms	28.8 ms	28.7 ms	···	19.0 ms
$d^{\rm LVD}$	26.8 ms	27.5 ms	0.9 ms	···	28.7 ms	16.9 ms
$d^{\rm IceCUBE}$	20.8 ms	15.6 ms	16.5 ms	16.9 ms	19.0 ms	···

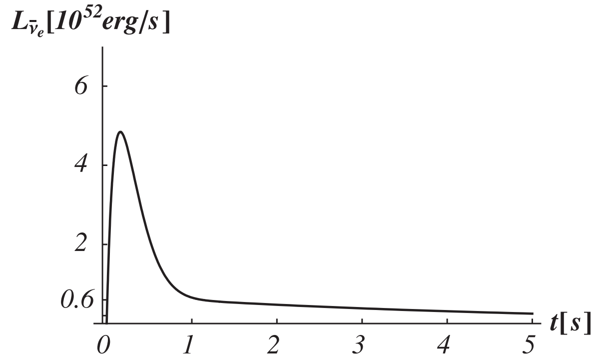

FIG. 1. The $\bar{\nu}_e$ luminosity in our model, for the choice of parameters used to generate the events. The initial phase of increased luminosity, called "accretion phase" and connected to the explosion, is clearly visible.

$$\begin{array}{lll} R_c = 16\ \text{km} & T_c = 4.6\ \text{MeV} & \tau_c = 4.7\ \text{s} \\ M_a = 0.22 M_\odot & T_a = 2.4\ \text{MeV} & \tau_a = 0.55\ \text{s} \end{array} \tag{5}$$

that are at odds with the theoretical expectations. For the rise-time scale we choose the intermediate value $\tau_r = 100$ ms [23]. The expected inverse beta decay events rate is $R(t, E_\nu, D) = N_p \sigma_{\bar{\nu}_e p}(E_\nu) \Phi_{\bar{\nu}_e}(t, E_\nu, D) \epsilon(E_{e^+})$, where D is the SN distance, N_p is the number of target protons within the detector, $\sigma_{\bar{\nu}_e p}$ is the process cross section, and ϵ is the detector efficiency function. We show in Fig. 2 the cumulative curve for an energy threshold $E_{\rm thr} = 6.5$ MeV and constant detection efficiency. We note that in the first 100 ms we expect to accumulate 5% of the total data set. This puts a limit on the detector mass and/or on the SN distance needed to fit successfully the parameter τ_r (as a rule of thumb, we need at least 20–30 events on average during the rise of the signal).

The total number of detected SN events is the integral of the rate R over time and energy. For a detection time window of 30 s the number of expected events in a detector with the same mass of SK (i.e., 22.5 kton of water) and efficiency $\epsilon = 0.98$ is

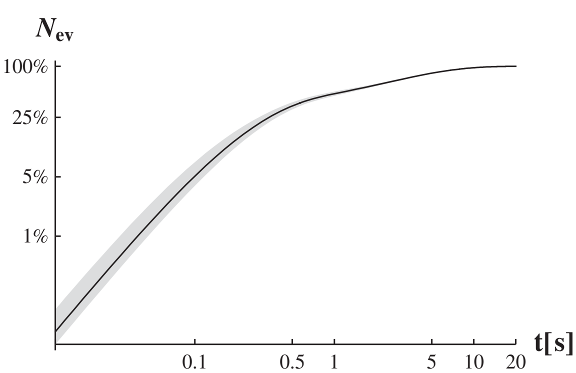

FIG. 2. Curve of events accumulation. The stripe is obtained varying the rise time τ_r in the interval given in the text.

$$N(D) = 4233 \left(\frac{10\ \text{kpc}}{D} \right)^2 \quad \text{for } E_{\rm thr} \geq 6.5\ \text{MeV}. \tag{6}$$

Thus, a SN neutrino burst from a galactic SN will be unmistakably identified.

Now we discuss the events generator. We extract a set of data from the rate function $R(t, E_\nu, 20)$, expected for a SN event at 20 kpc, which is a conservative or even pessimistic assumption. Each event is characterized by the relative detection time t_i (namely the time elapsed from the first detected event) and by the positron energy E_i; the error on this energy is given by the function $\delta E_i / E_i = 0.023 + 0.41\sqrt{\text{MeV}/E_i}$ [19].

Each data set was analyzed with the maximum likelihood procedure described in Ref. [20]. In this way we evaluated the best-fit values of the unknown parameters, including the one in which we are interested, $t_{\rm resp}$. The results for the astrophysical parameters are given in Table II. The good agreement with the true values of Eq. (5) proves that the procedure of analysis works properly. The rise time is also correctly estimated, $\tau_r = 105 \pm 37$ ms; the relatively wide error is due to the limited number of events and decreases for a closer SN.

Finally, the results for $t^{\rm fit}_{\rm resp}$ are given in Table III. In the first column are the true values of the response time $t^{\rm true}_{\rm resp}$, namely, the interval of time between the first neutrino detected and the first neutrino that arrived in the detector. In the second column are the corresponding best-fit values as determined from the maximization of the likelihood of the simulated data set and the statistical errors found by Gaussian procedure. The third column shows the difference between the true value and the estimated one, namely, the *true* error of our procedure. The fourth column gives the 1σ range of error, $2\delta t^{\rm fit}_{\rm resp}$, as evaluated from the second column. This is compared with the true error in the fifth column, by means of the compatibility error factor $C = |t^{\rm true}_{\rm resp} - t^{\rm fit}_{\rm resp}| / (2\delta t^{\rm fit}_{\rm resp})$. When this is lower than 1 the com-

TABLE II. Results of the analysis of ten simulated data sets for a SN event at 20 kpc. In the first column there is the number of SN events extracted. In the subsequent six columns are the best-fit values for the astrophysical parameters.

$N_{\rm SN}$	R_c (km)	T_c (MeV)	τ_c (s)	M_a ($M_\odot$)	T_a (MeV)	τ_a (s)	τ_r (ms)
977	14	4.7	4.6	0.16	2.4	0.63	51
1022	15	4.6	4.8	0.24	2.3	0.56	86
1110	14	4.8	4.7	0.18	2.4	0.61	99
1075	15	4.7	4.6	0.17	2.5	0.61	79
1101	16	4.6	4.7	0.19	2.4	0.56	104
1133	15	4.7	4.8	0.21	2.4	0.59	69
1101	16	4.6	4.8	0.35	2.3	0.48	166
1048	16	4.6	4.6	0.17	2.5	0.57	100
1069	16	4.6	4.7	0.18	2.5	0.55	126
1086	17	4.5	4.8	0.21	2.5	0.55	172

TABLE III. Results of the ten simulations. In the first column are the true values of the response times, and the second column shows the estimated ones. In the third column we report the true error and the fourth column the 1σ estimated ones. In the last column we show the values of the compatibility error factor.

$t_{\rm resp}^{\rm true}$ (ms)	$t_{\rm resp}^{\rm fit}$ (ms)	$\lvert t_{\rm resp}^{\rm true} - t_{\rm resp}^{\rm fit}\rvert$ (ms)	$2\delta t_{\rm resp}^{\rm fit}$ (ms)	C
13	$6^{+6}_{-4}[1\sigma]^{+13}_{-6}[2\sigma]$	7	9	0.78
11	$7^{+14}_{-7}[1\sigma]^{+19}_{-13}[2\sigma]$	4	22	0.16
9	$9^{+5}_{-4}[1\sigma]^{+13}_{-7}[2\sigma]$	0.3	9	0.03
13	$5^{+4}_{-3}[1\sigma]^{+10}_{-5}[2\sigma]$	7	7	1.00
5	$7^{+5}_{-4}[1\sigma]^{+13}_{-6}[2\sigma]$	3	9	0.29
6	$5^{+4}_{-2}[1\sigma]^{+10}_{-5}[2\sigma]$	0.8	6	0.13
13	$5^{+5}_{-5}[1\sigma]^{+11}_{-9}[2\sigma]$	7	10	0.70
23	$11^{+7}_{-4}[1\sigma]^{+14}_{-8}[2\sigma]$	12	11	1.10
3	$6^{+6}_{-3}[1\sigma]^{+13}_{-6}[2\sigma]$	2	9	0.29
2	$11^{+7}_{-4}[1\sigma]^{+16}_{-8}[2\sigma]$	9	11	0.85

patibility is good and the 1σ statistical error can be used to find the true value of the response time. The results show that this is the case. Thus, we can estimate the true time of the bounce with an average uncertainty time window of $\langle 2\delta t_{\rm resp}^{\rm fit}\rangle = 10.5$ ms.

Summary.—In quadrature the errors of the terms in Eq. (1), the time of the bounce, can be located in a temporal window of about 15 ms for a SN at 20 kpc.

Conclusions.—A galactic SN will permit us to obtain very detailed information on the time structure of the neutrino burst, thanks to large detectors as SK (capable of identifying the direction of the SN even in the absence of an astronomical observation), a lucky configuration between LVD-Virgo (practically in the same location), and new detectors such as IceCUBE.

We proved that it is possible to use the neutrino data to predict the time of the burst of gravity waves with a precision comparable to its expected duration. In more detail, the use of Eq. (1) allows the determination of the time of the bounce with a precision of few tens of milliseconds even for a galactic SN exploding at a distance of 20 kpc from us. While the proposed method mostly relies on the analysis of the conventional inverse beta decay events, we have argued that the ES events detected by SK could add valuable information.

Moreover, this type of analysis can be useful *even if* the ES events cannot be identified. Indeed, the large number of events detected by SK and IceCUBE allows us to deduce the astrophysical parameters that describe the observable neutrino signal, including the most crucial one, namely, the rise time τ_r. This information, inserted as a "prior" in the analysis of LVD data, greatly enhances the capability of our procedure to deduce with good precision $t_{\rm resp}$ from the relatively smaller LVD data set. The response time, determined in this way, can be used as a reliable trigger for the search of GW in Virgo.

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