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 ten milliseconds the time of the bounce, which is strongly correlated to the time of the maximum amplitude of the gravitational signal. This allows to precisely identify the gravitational wave burst timing.

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Introduction: Neutrinos and Gravitational Waves (GW) are emitted deep inside the Supernova (SN) core and reach terrestrial detectors practically unmodified. They are unique probes to obtain information on the still puzzling scenario of the explosion, in particular on multidimensional dynamics of the proto-neutron star and on the physics of the postshock region.

GW have not been observed directly yet 1, 2, 3, but detectors of enhanced sensitivity will operate in the forthcoming years. One of their aims is the search of GW bursts from core collapse SNe. An external trigger can be a very precious (or just necessary) tool for a successful search of such an impulsive sources of GW. In fact, an external trigger permits GW detectors to lower the event detection threshold, reaching a higher detection probability at a fixed false alarm probability 4, 5, 6.

The neutrino signal from a core collapse supernova has been detected for SN1987A. Despite low statistics and doubts, it can be said that these observations are in overall agreement with the expectations 7, 8; even more, they provide some support 9, 10 to the existence of a brief phase of intense neutrino luminosity expected in the standard scenario. Several detectors are ready to detect the future galactic SN and to test into details the physics of the explosion: when this signal will be available, using a proper analysis procedure, it will presumably become the external trigger for the search of a GW burst.

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 future galactic supernova. We argue that the size of this window, dictated by astrophysics, 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 GW and neutrinos: GW 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 11, 12, 13 show that this gravitational signal is emitted when the homologous collapse of the inner core halts, as dictated by the stiffening of the equation of state at nuclear density, and the bounce is pressure-dominated without strong influence of the rotation. Therefore, it is possible to define a generic GW waveform which exhibits a positive pre-bounce 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 14.

The duration of this signal is about 10 ms. Therefore, our goal is the identification of 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 (U.T.). We have:

$$T_{\text{source}} = T_{\text{int}} - t_{\text{GW}} - t_{\text{b}} - t_{\text{e}} - t_{\text{exp}}$$

where $T_{\text{source}}$ and $T_{\text{int}}$ are the absolute times, in U.T., of the bounce expected in the gravitational detector and of the first neutrino event detected by the neutrino detector, respectively. The time $t_{\text{GW}}$ 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 $t_{\text{GW}} = (1.5 - 4.5)$ ms 14. The time $t_{\text{max}}$ 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 $t_{\text{max}} \approx 0.27 \left( \frac{m_{\nu}}{0.03 \text{ eV}} \right)^2 \left( \frac{10^{-4} \text{ MeV}}{\nu} \right)^2 \left( \frac{D}{10 \text{ kpc}} \right)$ ms; thus, $t_{\text{max}}$ appears negligible. The time interval $t_{\text{e}}$ is the time of fly between the two detectors and depends on the SN position in the sky. Finally the non-negative parameter $t_{\text{exp}}$ is the difference of time between the first neutrino and the first event detected. In summary, the main terms in

1 Here and in the following times in uppercase are absolute times whereas times in lowercase are relative intervals of time.
Eq. 1 are the fly time $t_{\text{fly}}$ and the response time $t_{\text{resp}}$; 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 $\delta T_{\text{bounce}}$ and $\delta T_{\text{mt}}$ of the detector clocks are lower than $\mu s$; so their uncertainties can be neglected for our purposes.

**Measuring $t_{\text{fly}}$:** The time of fly between a neutrino and a GW detector separated by the distance $\Delta$ is $t_{\text{fly}} = \Delta \hat{n}$, where $\hat{n}$ is the direction pointing to SN. The error is negligible for an astronomically identified SN. The same when we consider the distance between LVD and VIRGO, $\Delta < 1$ 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 Tab. I) that could imply an error as large as $\sim 60$ ms. Thus we consider $\hat{n}$ as a random variable with most probable value $\hat{n}_{m}$ and find for $\delta \theta^{2}_{\text{fly}} = (t^{2}_{\text{fly}}) - (t_{\text{fly}})^{2}$:

$$\delta \theta^{2}_{\text{fly}} = \left( \hat{n}^{2} - (\hat{n}_{m})^{2} \right) \sin^{2}\theta \frac{1}{2} + (\hat{n} \hat{n}_{m})^{2} \left( \cos^{2}\theta - \left( \cos \theta \right)^{2} \right)$$

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

Tomas et al. [17] remarked that it is possible to do this with the elastic scattering (ES) events of SK. E.g., consider a SN at $20$ kpc. The search of the expected 35 forward ES events [17, 20] is simplified by minimizing the number of inverse beta decay (IBD) events. These could be diminished by 20% tagging the neutron [18] and again by 20%, requiring a visible energy lower than 30 MeV [8, 19]. In fact, due to the neutrino in the final state, the ES events have a low average energy of $\sim 15$ MeV [20] and an angular resolution $\delta \theta = 21^\circ$ [21]. By simulating and then fitting the events we estimate the error in the reconstructed direction. The average error on the angle is $5^\circ \pm 4^\circ$; only 60 out of 10,000 simulations had a reconstructed angle larger than $20^\circ$, occasionally due to a downward fluctuation of ES events. Thus, even in absence of an astronomical identification, it should be possible to determine the direction of the SN precisely enough to reduce the error $\delta \theta$ to the desired level. For a closer SN, larger number of ES events and/or better neutron identification, the measurement will be safer.\(^2\)

**Measuring $t_{\text{resp}}$:** The value of $t_{\text{resp}}$ 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 parameterized 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 SN1987A data analysis [10]. 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:

$$\Phi_{\bar{\nu}_{e}}(t) = f_{r}(t)\Phi_{a}(t) + (1 - j_{k}(t))\Phi_{e}(t - \tau_{a}).$$

Here $t$ is the relative emission time, while $\Phi_{a}$, $\Phi_{e}$ and $j_{k}(t)$ are the accretion flux, the cooling flux and the function that links the two emission phases, respectively.\(^3\)

The expected rise [16] is described introducing:

$$f_{r}(t) = 1 - e^{-t/\tau_{r}}$$

that improves the existing parameterizations [8, 10]. The time scale $\tau_{r} \sim 50 - 300$ ms depends strongly [18, 22] on the velocity of the shock wave; $\tau_{r}$ is the new, crucial model parameter. The accretion flux $\Phi_{a}$ is generated by

\(^2\) To facilitate the search for the SN direction further, one could restrict the search to the galactic plane.

\(^3\) The model is based on Section 3 of [10]. Various source codes that implement this model can be downloaded at the address [http://theory.lngs.infn.it/astroparticle/sn.html](http://theory.lngs.infn.it/astroparticle/sn.html)
the interactions between the neutrons and the positrons above the shock and is described by 3 parameters: the initial accreting mass ($M_a$), the time scale of the accretion phase ($\tau_a$), and the initial temperature of the $e^+$ ($T_a$). The cooling flux $\Phi_e$ coming from the thermal emission of the new born proto-neutron star is proportional to the radius of the neutrino sphere ($R_e$), shows a time scale ($\tau_e$), and an initial temperature of the emitted antineutrinos ($T_e$). In summary, our parametrization of the $\nu_e$ emission model includes 7 astrophysical parameters.

In order to construct a Monte Carlo simulation of a future SN event, we select the best-fit values of the parameters found from SN1987A data analysis [10], namely

$$R_e = 16^{+9}_{-5} \text{ km}, \quad M_a = 0.22^{+0.68}_{-0.15} M_\odot,$$

$$T_e = 4.6^{+0.7}_{-0.6} \text{ MeV}, \quad T_a = 2.4^{+0.6}_{-0.4} \text{ MeV},$$

$$\tau_e = 4.7^{+1.7}_{-1.2} \text{ s}, \quad \tau_a = 0.55^{+0.58}_{-0.17} \text{ s},$$

that are at odds with the theoretical expectations. For the rise-time scale we choose the intermediate value $\tau_r = 100 \text{ ms}$ [22]. The expected IBD events rate is:

$$R(t, E_{\nu}, D) = N_p \sigma_{\nu_p p} (E_{\nu}) \Phi_{\nu_e} (t, E_{\nu}, D) \epsilon (E_{e^+}),$$

where $D$ is the SN distance, $N_p$ is the number of target protons within the detector, $\sigma_{\nu_p p}$ is the process cross section and $\epsilon$ is the detector efficiency function. We show in Fig. 2 the cumulative curve for an energy threshold $E_{\text{thr}} = 6.5 \text{ MeV}$ 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 $\tau_e$ (as a thumb rule, 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 function in the energy and in the detection time. For a detection time window of 30 seconds 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

$$N(D) = 4233 \left( \frac{10 \text{ kpc}}{D} \right)^2 \text{ for } E_{\text{th}} \geq 6.5 \text{ MeV},$$

FIG. 2: Curve of events accumulation in semilogarithmic scale. The slow (approximately quadratic) initial accumulation is well visible. The bump at $\sim 0.5 \text{ s}$ is due to the accretion phase.

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

Now we discuss the details of the analysis procedure. We extract a set of data from the rate function $R(t, E_{\nu}, 20)$, expected for a SN event at 20 kpc, that is a conservative or even pessimistic assumption. Each event is characterized by the relative detection time $t_i$ (namely the interval time elapsed from the first detected event) and by the positron energy $E_i$; the error on this energy is obtained from the smearing function $\delta E_i / E_i = 0.023 + 0.41 \sqrt{\text{MeV} / E_i}$ [21]. Finally we analyze the data set using a maximum likelihood procedure to find the best-fit values of the 7 free astrophysical parameters of the emission model described above, together with the $t_{\text{resp}}$ parameter, the quantity that we want to estimate. For each simulated data set we obtain from the fit a value of this last parameter, that we call $t_{\text{resp}}^{\text{fit}}$. We will compare this fit value with the true value, that we call $t_{\text{resp}}^{\text{true}}$, and in this way, we will be able to validate the procedure of analysis.

We show in Tab. II the best-fit values of the astrophysical parameters for ten simulated data sets, each one comprising $N_{\nu_S}$ data for a SN event at 20 kpc and we compare them with the true values in Eq. [5] used for the event generator. The comparison of the best-fit values for the astrophysical parameters can be used to test the validity of the statistical procedure; it is remarkable that all these best-fit values are well within the 1$\sigma$ statistical errors found in [10] and reported in Eq. [5].

The results for $t_{\text{resp}}^{\text{true}}$ are given in Tab. III In the first column there are the true values of the response time $t_{\text{resp}}^{\text{true}}$, namely the interval of time between the first neutrino detected and the first neutrino 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.

| $N_{\nu_S}$ | $R_e$ | $T_e$ | $\tau_e$ | $M_a$ | $T_a$ | $\tau_a$ | $\tau_r$ |
|-------------|-------|-------|---------|-------|-------|---------|---------|
| 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    | 4.7   | 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 II: Results of the analysis of ten simulated data sets for a SN event at 20 kpc. In the 1st column there is the number of SN events extracted. In the subsequent six columns are the best-fit values for the astrophysical parameters.
TABLE III: Results of the ten simulations. The 1st column are the true values of the response times, the 2nd column the estimated ones. In the 3rd column we report the true error and the 4th column the 1σ estimated ones. In the last column we show the values of the compatibility error factor.

| C   | \( t_{\text{resp}}^{\text{true}} \) [ms] | \( t_{\text{resp}}^{\text{est}} \) [ms] | \( t_{\text{resp}}^{\text{true}} - t_{\text{resp}}^{\text{est}} \) [ms] | 2\( \sigma \)t_{\text{resp}}^{\text{est}} [ms] |
|-----|---------------------------------|---------------------------------|---------------------------------|------------------|
| 13  | 6.86 \( +1.16 \) [1σ] \(-6.3\) [2σ] | 7                               | 9                               | 0.78             |
| 11  | 7.57 \( +1.63 \) [1σ] \(-7.3\) [2σ] | 4                               | 22                              | 0.16             |
| 9   | 9.55 \( +1.87 \) [1σ] \(-7.3\) [2σ] | 0.3                             | 9                               | 0.03             |
| 13  | 5.34 \( +2.5 \) [1σ] \(-5.7\) [2σ] | 7                               | 7                               | 1.00             |
| 5   | 7.4 \( +2.3 \) [1σ] \(-6.1\) [2σ] | 3                               | 9                               | 0.29             |
| 6   | 5.34 \( +2.5 \) [1σ] \(-5.7\) [2σ] | 0.8                             | 6                               | 0.13             |
| 13  | 5.27 \( +1.5 \) [1σ] \(-8.9\) [2σ] | 7                               | 10                              | 0.70             |
| 19  | 11.56 \( +1.7 \) [1σ] \(-7.3\) [2σ] | 12                              | 11                              | 1.10             |
| 13  | 6.86 \( +1.16 \) [1σ] \(-6.3\) [2σ] | 2                               | 9                               | 0.29             |
| 11  | 11.56 \( +1.7 \) [1σ] \(-7.3\) [2σ] | 3.9                             | 11                              | 0.85             |

Discussion: 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 to indentify the direction of the SN even in absence of an astronomical observation), thanks to a lucky configuration between LVD-Virgo (practically in the same location) and possibly thanks to new detectors such as IceCUBE.

We have shown that even in rather conservative assumptions, namely for a very distant galactic SN, it will be possible to use the neutrino data to predict the time of the burst of gravity waves with a precision comparable to its expected duration. More in detail, the use of Eq. II 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 elastic scattering (ES) events detected by SK could add precious information.

However, this type of analysis can be useful even if a sample of ES events cannot be precisely 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 \( \tau_r \). This information, inserted as a “prior” in the analysis of LVD data, greatly enhances the capability of our procedure to deduce with good precision \( t_{\text{resp}} \) 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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