Using supernova neutrinos to monitor the collapse, to search for gravity waves and to probe neutrino masses

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We discuss the importance of observing supernova neutrinos. By analyzing the SN1987A observations of Kamiokande-II, IMB and Baksan, we show that they provide a 2.5σ support to the standard scenario for the explosion. We discuss in this context the use of neutrinos as trigger for the search of the gravity wave impulsive emission. We derive a bound on the neutrino mass using the SN1987A data and argue, using simulated data, that a future galactic supernova could probe the sub-eV region.

Keywords: Supernova, neutrinos, gravitational waves.

Introduction  Core collapse supernovae (type II, Ib and Ic) occur when the progenitor has a mass $> 8 M_\odot$ and originate compact remnants: neutron stars, black holes and possibly hybrid (=quark core) stars. The formation of such an object requires to carry away a huge binding energy, several times $10^{53}$ erg. It is well known that the role of carriers is played mainly by neutrinos; but more importantly for us, and according to the standard scenario of core collapse supernova explosion\cite{12}, neutrinos play also a fundamental role in driving the explosion. They deposit energy that can revive the shock, which will eventually cause the expulsion of the external layers of the star.

The current scenario of neutrino emission is based on two main phases of neutrino emission. The first one, called accretion phase, entails 10-20% of the total energy. It is characterized by a very high neutrino luminosity and is directly related to the matter which is accreted over the proto-neutron star through the stalled supernova shock wave. The other phase is called cooling phase; the neutrinos escape slowly from the proto-neutron star, releasing the remaining 80-90% of the energy. Only two analyses of SN1987A data included both emission phases: the analysis of 2001 by Loredo and Lamb\cite{13} and the recent one due to our group\cite{3}. The most relevant modification of this last analysis is the improvement of the model of $\bar{\nu}_e$ emission
Fig. 1. Directions of events in a Cherenkov detector of 32 kton: the ∼ 300 elastic scattering events are visible over the ∼ 5000 inverse beta decay events, expected from the galactic center. [We use the Lambert projection: the points of the unit sphere—i.e., the possible directions—identified by \( n = (s_\theta c_\phi, s_\theta s_\phi, c_\theta) \), are mapped into the circle of radius 2, whose points are identified by \((u, v) = (c_\phi, s_\phi)\sqrt{2(1-c_\theta)}\); namely, \( u = n_x \frac{\sqrt{2}}{1-n_z} \) and \( v = n_y \frac{\sqrt{2}}{1-n_z} \). The Lambert projection conserves the areas, \( d\Omega = d\phi dc_\theta = d^2a = dudv \).

that we are going to describe in some detail in the following. Remarkably, both these analyses claim an evidence of the phase of accretion in the SN1987A data.

Detecting Supernova Neutrinos Before describing the model, we recall how many events we expect from the most important detection reaction, the inverse beta decay (IBD): \( \bar{\nu}_e + p \rightarrow e^+ + n \). The number of events is: \( N_{\text{ev}} = N_p \times F_{\bar{\nu}_e} \times \sigma_{\bar{\nu}_e p} \). The cross section for a \( \bar{\nu}_e \) with average energy \( \bar{E} = 15 \text{ MeV} \) is \( \sigma_{\bar{\nu}_e p} \approx G_F^2 \bar{E}^2 \approx 10^{-41} \text{ cm}^2 \).

The \( \bar{\nu}_e \) fluence (time integrated flux) can be written by \( F_{\bar{\nu}_e} = \frac{\bar{E}_0}{4\pi D^2} \approx \frac{2 \times 10^{57}}{10(50 \text{kpc})^2} \sim 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \), where \( \bar{E}_0 = 3 \times 10^{53} \text{ erg} \) is the gravitational binding energy, \( D \) is the distance of the supernova and “6” are the neutrino types. For 1 kton detector, there are \( N_p \approx 1 \text{ kton} \times 10^9 \times 6 \cdot 10^{21} \times 2/18 \times 10^{32} \) protons. So the number of expected events is about 10. This rough estimation agrees with the number of events observed: 16 in Kamiokande-II (2140 tons), 8 in IMB (6800 tons) and 5 in Baksan (200 tons): 29 events in 30 seconds, that include a few background events.

Other reactions are expected to yield less events in water Cherenkov (as Kamiokande-II, IMB, Super-Kamiokande) or scintillators (as Baksan, LVD, KamLAND). This is true, e.g., for the elastic scattering reaction, where the cross section \( \sigma_{\text{es}} \sim G_F^2 m_e E \) is much smaller since \( E \gg m_e \). However the electrons are scattered by supernova neutrinos in the same direction of the incoming neutrinos, for the same

\[ \text{Other features of the new analysis: (i) energy, time and direction of each event are taken into account; (ii) the correct background, finite detection efficiency and energy resolution are described; (iii) dead times and live time fraction are included; (iv) only the relative times are used and the delay of the detector response, called offset times, is accounted for; (v) frequentist techniques of inference are applied with an unbiased likelihood; and (vi) the full 30 s analysis window is considered. An updated cross section of IBD is used, an improved description of the neutrino spectrum is introduced and neutrino oscillations are accounted for in a suitable approximation.} \]
reason, $E \gg m_e$. In other words, elastic scatterings will allow ‘neutrino imaging’ as is illustrated in the figure, where we show the directions of arrival of the supernova events. The cluster of events in the center, due to elastic scattering, is well visible over the background of inverse beta decay events, which are only mildly directional. The statistical analysis shows that the direction of the supernova is determined with an accuracy of few degrees. See 11, 12, 6 for further discussion.

We close this introductory note remarking that supernova neutrinos are a special target of neutrino astronomy. Indeed, despite the rarity of the observable core collapses, these neutrino can be certainly detected as demonstrated by SN1987A; moreover, they will permit to shed light on many open theoretical problems, regarding several fields: astrophysics, nuclear physics and particle physics.

**Model of Neutrino Emission** We describe now the model for the neutrino flux. Each emission phase is characterized by its intensity, its duration and the average energy of the emitted neutrinos. So, we have 6 astrophysical parameters, namely: the initial mass ($M_a$), the time scale ($\tau_a$) and the initial temperature ($T_a$) for the accretion phase; the radius ($R_c$), the time scale ($\tau_c$) and the initial temperature ($T_c$) for the cooling phase. Moreover, in order to take into account the delay of the first observed event with respect to the first neutrino, we introduced other free parameters, called *offset times*. Since the clocks of Kamiokande-II, IMB and Baksan were not synchronized, we need 3 offset times. For details, see 3.

The expectations on these astrophysical parameters are: $R_c \sim R_{ns} = 10^{-20}$ km, $T_c = 3 - 6$ MeV and the duration of the cooling phase should be few (or many) seconds. The accretion phase has $M_a < 0.6 M_\odot$, $T_a$ is the few MeV range and the accretion should last just $\sim 0.5$ s. The accretion $\bar{\nu}_e$ luminosity can be estimated by:

$$L_{\text{accr}} \sim N_n (\sigma_{\bar{\nu}_e+n}) T_a^4 \sim 5 \times 10^{52} \text{erg sec} \left( \frac{M_a}{0.1 M_\odot} \right) \left( \frac{Y_n}{0.6} \right) \left( \frac{T_a}{2 \text{ MeV}} \right)^6,$$

(1)

where $N_n$ is the number of neutrons, that can be expressed in term of an accretion mass, $M_a$, and of the fraction of neutrons in the environment, $Y_n$. The cooling $\bar{\nu}_e$ luminosity has instead the form:

$$L_{\text{cool}} \sim R_c^2 T_c^4 \sim 5 \times 10^{51} \text{erg sec} \left( \frac{R_c}{10 \text{ km}} \right)^2 \left( \frac{T_c}{5 \text{ MeV}} \right)^4,$$

(2)

where $R_c$ and $T_c$, are, respectively radius and temperature of the cooling. These formulae make evident that the two phases are described by very different physical models, namely, by a transparent atmosphere and by an opaque (black body) radiator; this is the reason why the first phase is much more luminous.

The two phases are not contemporaneous. We parameterize the $\bar{\nu}_e$ flux as follow:

$$\phi_{\bar{\nu}_e}(t) = \phi_a + (1 - j_k(t)) \times \phi_c(t - \tau_a).$$

(3)

Above $j_k$ represents a function that terminates the accretion phase at $t \approx \tau_a$, approximated by $\exp \left[-(t/\tau_a)^2\right]$. The flux is dominated by the accretion phase at
$t \ll \tau_a$, whereas the cooling phase begins at $t \approx \tau_a$ and eventually dominates the flux when $t \gg \tau_a$. With previous considerations in mind, we understand that Eq. (3) describes the passage from an emission of volume to an emission of surface. The spectrum is quasi-thermal at any time; furthermore, the neutrinos luminosity and their average energies are smooth functions of the time.

The best fit values of the astrophysical parameters of accretion and cooling emission phases are found to be:

- $R_c = 16^{+9}_{-5}$ km
- $M_a = 0.22^{+0.68}_{-0.15}$ $M_\odot$
- $T_c = 4.6^{+0.7}_{-0.6}$ MeV
- $T_a = 2.4^{+0.6}_{-0.4}$ MeV
- $\tau_c = 4.7^{+1.7}_{-1.2}$ s
- $\tau_a = 0.55^{+0.58}_{-0.17}$ s

The large errors are due to the limited statistics. The results are close to what we expect from the standard collapse, in particular we get $\mathcal{E}_b = 2.2 \times 10^{53}$ erg. There is a 2.5 $\sigma$ evidence for the accretion phase. The 11 early events of Kamiokande-II (6), IMB (3) and Baksan (2) have a great probability to belong to the accretion phase.

**Gravitational Waves and Neutrinos**

Gravity Waves (GW) are predicted by general relativity. They have not been observed directly yet, but we will have soon detectors of enhanced sensitivity. Core collapse supernovae can emit GWs during the collapse (or during the explosion) of a core collapse SN due to the change of the quadrupole moment of the star structure. Recent simulations show that a 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 pre-bounce rise and a large negative peak, followed by a ring-down; so the time of the bounce is strongly correlated to the time of the maximum amplitude of the gravitational signal.

The duration of the GW signal is about 10 ms. Therefore, to help the search of such signals, one would like to identify the time of the bounce with an error of the same order studying other types of signal emitted from this event. In ref. [11] it was argued that it is possible to identify the time of the bounce within $\sim 10$ ms by an analysis of the $\bar{\nu}_e$ signal from the explosion of a galactic core collapse supernova; i.e., neutrinos can provide the required trigger for the search of GW.

In fact, extensive simulations of core collapse SNe shows that the onset of $\bar{\nu}_e$ luminosity is closely related to the time of the bounce. The time of the bounce $T_{\text{bounce}}$ can be determined by the following equation, where the times in uppercase

\[ b \]

We add a remark on backgrounds events. The 6th-event of Kamiokande-II, with energy below 7.5 MeV, has a probability of 85% to be due to background; a posteriori, it should not be attributed to accretion. Similarly, we found that the $13^{th} - 16^{th}$ events are almost surely due to background and there is still some chance of another background event. Similarly in Baksan, where the number of events is larger than expected and this is quite likely a priori. In absence of more precise information, we assumed that IMB was background free; we checked that the inferences do not change significantly assuming that it had a background rate similar to the one of Kamiokande-II.
are absolute times, in UT, whereas those in lowercase are relative intervals of time:

\[ T_{\text{bounce}} = T_{1\text{st}} - (t_{GW} + t_{\text{mass}} + t_{\text{fly}} + t_{\text{off}}), \]  

(4)

\( T_{1\text{st}} \) is the time of the first neutrino event detected. The time \( t_{GW} \) is the interval between the bounce of the outer core on the inner core and the beginning of \( \bar{\nu}_e \) emission. This is reliably known and ranges within \( t_{GW} = 1.5 - 4.5 \) ms. The time \( t_{\text{mass}} \) is the delay, due to neutrino mass, between the arrival of GW and neutrino signal; if we impose the cosmological bound \( \sum_i m_{\nu_i} < 0.7 \) eV, this is negligible. The time interval \( t_{\text{fly}} \) is the time of fly between the two detectors and depends on the SN position in the sky. Finally the non-negative parameter \( t_{\text{off}} \) is the difference in time between the first neutrino and the first event detected. In summary, the main terms in Eq. (4) are the fly time \( t_{\text{fly}} \) and the offset (or response) time \( t_{\text{off}} \).

For the analysis of a future galactic supernova event, it is important to consider the finite rising time of the \( \bar{\nu}_e \) signal. This can be done multiplying the flux of Eq. (3) by the function \( f_r = 1 - e^{-t/\tau_r} \). The rising time \( \tau_r \approx 50 - 150 \) ms is a very important and new parameter of the astrophysical model. It is related with the initial production of \( \bar{\nu}_e \) and depends strongly on the velocity of the shock wave.

How to determine experimentally the time of fly from neutrinos? If we know astronomically the direction of the SN, it is easy to correct for the difference of arrival times. But even if we do not know it, we can rely on elastic scattering (ES) events, that are directional and suffice to determine the time of fly precisely enough. (Note in particular that this can be applied to a supernova without optical output).

Thus, the problem reduces to the estimation of \( t_{\text{off}} \), i.e., the delay of the response of the detector to the neutrino signal. If we have enough data and if we reconstruct at the same time \( \tau_r \), it is possible to reconstruct successfully \( t_{\text{off}} \) by fitting the data to the expectations. As we can see from Table 3 of the reference [11], these conditions are expected to be satisfied for a galactic supernova event: The response time and its error are correctly estimated by the analysis. We conclude that the future galactic supernova can provide us a precious information to test a key prediction of general relativity and note incidentally, again from [11], that also the other astrophysical parameters will be reconstructed with very good precision.

Neutrino Mass It is known since Zatsepin [14] that supernova neutrinos permit us to investigate the absolute mass scale of neutrinos. Several works attempted this after SN1987A: see the Table for a partial review [15,16]. We will mostly discuss the last two entries of this Table, but before doing that, we recall the idea.

The flux, Eq. (3), is a function of the emission time \( t_i \), namely the time measured from the beginning of antineutrino emission. In terms of the absolute emission times we have \( t_i = T_i^e - T_0^e \), that can be rewritten taking into account the velocity of the neutrino \( v_i \) and the absolute detection time \( T_i^d \) as follows:

\[ t_i = \left( T_i^d - \frac{D}{v_i} \right) - \left( T_0^d - \frac{D}{c} \right) \approx \left( T_i^d - T_1^d \right) + \left( T_1^d - T_0^d \right) - \frac{D}{2c} \left( \frac{m_{\nu} c^2}{E_{\nu,i}} \right)^2 \]  

(5)
where $T_d^0$ is the minimum, possible detection time. The first term in the r.h.s. $T_i^d - T_0^d = \delta t_i$ is known from the experiment. The second one, $T_1^d - T_0^d = t_{\text{off}}$ is by definition the offset time, namely the delay between the first observed event and the moment when the first neutrino has possibly reached the detector. The last one, denoted by $\Delta t_i$, describes the effect of the finite neutrino mass. Its numerical expression is:

$$\Delta t_i = 2.6 \text{ sec} \times \frac{D}{50 \text{ kpc}} \left( \frac{m_\nu c^2}{10 \text{ eV}} \right)^2 \left( \frac{10 \text{ MeV}}{E_{\nu,i}} \right)^2.$$ (6)

Putting together the above definitions, the emission time of each event, that enters the likelihood through the antineutrino flux, will be written as:

$$t_i = \delta t_i + t_{\text{off}} - \Delta t_i.$$ (7)

Again, the first term in the r.h.s. is the relative time between the $i$-th and the first observed event in the considered detector, known directly from the data without significant error. The last two terms, instead, have to be estimated by fitting the data; both of them are positive (and thus lead to some cancellation) but depend in a different way from the neutrino energy, see Eq. (6). $E_{\nu,i}$, in turn, can be inferred from the measured energy of the positron, $E_i$, which is known up to its error $\delta E_i$.

From our statistical analysis\cite{16}, we obtain from SN1987A data the bound

$$m_\nu < 5.8 \text{ eV at } 95\% \text{ CL.}$$ (8)

The existence of a phase of accretion of about 0.5 s explains why we are able to probe such neutrino masses. From Eq. (6) it should be evident that the most important information to determine the mass is contained in the first, low energy events. This consideration selects as most relevant the events of Kamiokande-II, which incidentally, are also the events that probe the existence of the accretion phase. The astrophysical uncertainties are not very relevant; instead, the fact that
offset time is unknown contributes to worsen the bound. Note that the agreement of the last two entries of the table is to a large extent accidental; e.g., the bound changes by 5 – 10% adopting other conventional statistical procedures.

By mean of simulated data, we demonstrated the possibility to probe sub-eV neutrino masses with Super-Kamiokande after a future galactic supernova. As discussed in, this limit requires a very precise knowledge of the time and it is subject to strong fluctuations, related to the position of the first low energy event.

**Remark on the Relevant Time Scales** We would like to summarize here the above results emphasizing the role of the relevant ‘time scales’:

1) We recalled that the conventional astrophysical picture of the explosion contains a relatively short time scale, namely the duration of the accretion \( \tau_a \sim 0.5 \) s. We argued that SN1987A data already provide some evidence for this time scale, thanks to the fact that almost 40% of the observed events fall in this phase. A future galactic supernova will give us a much better determination of the astrophysics and plausibly also of 10 ms (or even few ms) structures in the signal.

2) The search for GW can profit of the detection of neutrinos. We remarked that the observation of a future galactic supernova neutrino event could permit a determination with 10 ms precision of the moment of the bounce, when a burst of GW is plausibly emitted. (The same cannot be done for SN1987A, since the absolute time of the events is unknown, except for IMB; thus, the bounce should have occurred 0.76 s before the first event seen by IMB, see Eq. (32) of). The postulated rise time of the signal, of the order of 50-150 ms, can also be measured.

3) The determination of the neutrino mass has to go through a precise determination of times: see Eq. (1); the smaller the time scale we probe, the better the limit on the mass we obtain. E.g., the bound from SN1987A (several eV) is essentially determined by the existence of an accretion phase, while for a future supernova the relevant time scale will be the rise time of the signal (probing the sub-eV region). This could be further improved detecting a hypothetical shorter burst of \( \bar{\nu}_e \), lasting only few ms. This is not expected to exist for a standard collapse, but it has been found in the first numerical simulations concerning the formation of a hybrid star.

**Conclusions** The problem to explain SN explosion is still open, however, a reference (standard) model does exist. In this work, we focussed on this standard scenario and discussed possible observational tests.

The SN1987A data present unexpected features, however, KII, IMB and Baksan data fit in a specific model. They show a hint of an initial high-luminosity phase, as the one expected for a standard neutrino emission. A future galactic SN will permit much more precise tests providing a huge amount of new information; remarkably,

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\(^{c}\)This is a significant extension of the usual approach to SN1987A data analysis (as summarized, e.g., in Bahcall book) where the neutrinos are thought to originate from a smooth, thermal emission with a much longer time scale, \( \tau_c \) = several seconds.
it will also give the GW burst timing within $\sim 10$ msec. Also it will be possible to establish a relatively tight neutrino mass bound, up to the sub-eV range.

Finally, we noted that many of the interesting results on astrophysics and particle physics that can be obtained by observations of supernova neutrinos are essentially based on precise measurements of time. This consideration emphasizes the crucial importance to improve our knowledge on the astrophysics of the neutrino emission.

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