A Parameterized Model for Supernova Electron Antineutrino Emission and Its Applications

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Abstract. We discuss a parameterized model that describes the electron antineutrino flux emitted by core collapse supernovae. We illustrate its flexibility showing that it can be used to obtain: 1) evidence for an initial increase of the neutrino luminosity from SN1987A; 2) refined neutrino mass bounds; 3) a tool to simulate and analyze data; 4) the proof that neutrinos are an effective trigger for GW search; 5) expectations and theoretical errors for the diffuse neutrino background. Some results obtained with this model are shown in Table 1.

Table 1. Sample results based on the model of refs. [1, 3].

| Analysis of SN1987A | Duration of the accretion $\tau_a = 0.55$ s\textsuperscript{[1]} |
|---------------------|-------------------------------------------------|
|                     | Neutrinosphere radius $R_c = 16$ km\textsuperscript{[1]} |
|                     | Neutrino mass $m_\nu < 5.8$ eV\textsuperscript{[2]} |

| Future supernova | Duration of the accretion $\delta\tau_a/\tau_a = 10\%$\textsuperscript{[3]} |
|------------------|------------------------------------------------|
|                  | Neutrinosphere radius $\delta R_c/R_c = 5\%$\textsuperscript{[3]} |
|                  | Neutrino mass $m_\nu < 1$ eV\textsuperscript{[2]} |

| Gravity Wave Burst | Time of the burst $\delta t < 15$ ms\textsuperscript{[3]} |
|-------------------|-------------------------------------------------|

| Diffuse Background | Counting rate in SK $(0.3-0.9)/$yr\textsuperscript{[4]} |
|--------------------|-------------------------------------------------|
|                    | Counting rate in SK+ $(1.1-2.9)/$yr\textsuperscript{[4]} |

1. An improved parameterized model

1.1. Necessity of improvements

There is a high chance that, in the next $50\pm20$ years, neutrinos from a galactic core collapse supernova will bless Super-Kamiokande, KamLAND, Baksan, LVD, Borexino, MiniBOONE, IceCUBE and/or future detectors. Super-Kamiokande (SK) alone will see $1,000$-$100,000$ events, at least 2 orders of magnitudes greater than seen from SN1987A. This will lead to progresses that we can be barely imagine today; what it is easy to imagine is that we will use models for the neutrino emission to extract information from the data.
Many papers on supernova neutrinos adopt, without an adequate discussion, the same simplified model for the neutrino flux. Up to non-thermal effects, this model describes just a black body emission:

\[ \Phi_{\bar{\nu}_e} \propto R_c^2 \times E^2 \times e^{-E/T} \]  

and it takes into account the fact that the signal has a limited temporal extension by prescribing \( T = T_c e^{-t/\tau_c} \) and \( R_c = \text{const.} \) or similar time evolutions. We refer to this description as the “exponential cooling model”. Often, the model is simplified even further: time evolution is ignored altogether and only the energy spectrum is considered.

The exponential cooling model has been almost universally used for the analyses of SN1987A data (with just two exceptions, see below). Our criticisms to this model are the following:

- It does not resemble the expectations.
- It is likely to be inadequate for future supernova.

These are not minor concerns. The upper panel of Fig. 1 shows the luminosity found in a numerical simulation of the emission [5]. We have a smooth evolution of the luminosity, that somewhat resembles an exponential cooling, but only after half a second. In the first half second, the luminosity is much larger. The exponential cooling model, alone, does not provide us with an adequate modeling of the flux; while this model could be adequate for some applications, it is evident that some basic information about the time distribution is missing.

![Figure 1](image_url)  

**Figure 1.** A typical outcome of a numerical simulation. In the upper panel, the luminosity (i.e., power) radiated in neutrinos of all types; in the lower panel, their average energy. From Totani, Sato, Dalhed, Wilson [5].

1.2. The improved model

Let us begin by outlining the physical picture of the emission. Following Loredo & Lamb [6], we aim to describe the transition from an intense initial emission to a black-body emission. The nature of the neutrino emission is assumed to change according to this scheme:

**Volume → Surface**

i.e., we pass from an emission by a transparent atmosphere to the usual surface emission of a black-body. We illustrate the conditions during the initial stages of neutrino emission, as depicted in Figure 2. Just after the collapse, rapid accretion processes will produce a thermalized electromagnetic plasma composed of \( \gamma, e^-, e^+ \), which yields copiously \( \bar{\nu}_e \) through

\[ e^+ + n \rightarrow p + \bar{\nu}_e. \]  

We assume that the \( \bar{\nu}_e \) can escape freely. This means that only a certain fraction of the neutrons, the ones around the nascent neutron star, will effectively act as targets for the collisions of the
2. Applications

2.1. A new fit of SN1987A neutrino data

A fit to the SN1987A data collected by Kamiokande-II, IMB and Baksan, based on our model, has been performed in [1]. The fit returns an antineutrino flux quite similar to the simulations. In particular, the luminosity is an order of magnitude larger in the first half of a second, as expected in the standard scenario for the emission. The total energy is estimated to be $2.2 \times 10^{53}$ erg;\footnote{However, this result is heavily based on the hypothesis of equipartition. It will be an important experimental challenge to extract this quantity, with minimum theoretical bias, from the data of a future supernova.} for a discussion of the importance of this quantity, see [8]. The new model describes the data $2.5 \sigma$ better than the exponential cooling model after accounting for the larger number of parameters. A sensible question is: what is the reason of the improvement? In particular, is it caused by some subtlety in the statistical analysis or does it depend on a specific feature of the data themselves?
The correct interpretation is the second one, as clear from the time distribution of the observed events given in Figure 4: the initial peak, comprising 30% of the detected events, indicates an increased electron antineutrino luminosity in the first instants of the emission.

**Figure 4.** Cumulative distribution of SN1987A events as a function of the time from the first one [9]. The remarkable, initial peak of events is readily explained by the increased luminosity expected in the standard emission. We show only the events of Kamiokande-II, IMB and Baksan that, within errors, can be interpreted as almost simultaneous. The first event of each detector coincide: in fact, the clocks of Kamiokande-II and Baksan gave the absolute time only within large errors, thus the times among different detector acquire meaning only after the fit. We do not attempt an interpretation of LSD data.

2.2. *A tool to simulate and analyze the response to a future supernova*

Once we have a parameterized model [10], we can produce sets of simulated events and use them to validate a procedure of analysis or to estimate whether an experiment will permit us to understand a certain phenomenon. We show in Fig. 5 an example of a simulated dataset in a detector with 22.5 kton mass of water. Its analysis suggests that, with a future supernova, a precise determination of the astrophysical parameters will be possible. The physics of the emission and, in particular, the existence of the intense initial emission of the Bethe & Wilson+Nadyozhin scenario, will be probed much more accurately. In fact, even from 20 kpc, we find \( \delta \tau / \tau \approx 10\% \). The small SN1987A dataset leads to a much larger error, \( \tau = 0.55^{+0.58}_{-0.17} \) s, though the central value agrees remarkably well with the expectations of the Bethe & Wilson+Nadyozhin scenario. For details, the main reference is [3].

2.3. *Neutrino mass and supernova events*

A finite mass implies that neutrinos with different energies have different velocities. If we know when the emission began, and if we see a neutrino event shortly after, we can put a strong bound on the mass, especially if its energy is low. However, in order to learn something about the masses, it is necessary to know something about the emission. Actually, it is enough to know the shape of the signal, up to the unknown parameters of the emission. Thus our parameterized model offers an appropriate tool to perform such an analysis. The duration of the accretion determines the bound on the mass shown in Tab. 1. For a future supernova, the limit can be improved up to about 1 eV. See [2, 7] for details and bibliography.

2.4. *A remark on supernova neutrino astronomy*

The main number of events in conventional detectors (including those which observed SN1987A) are those due to “inverse beta decays” (IBD) which is, actually, the inverse of the reaction in Eq. 2:

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]  

Generally, we do not know the beginning of neutrino emission. Thus, in the analysis of the data, we should consider as a free parameter the amount of time between the first neutrino arrived in the detector and the first neutrino signal that was detected. However, the delay due to neutrino mass should be determined by the same data. The two effects act in opposite senses, which creates numerical difficulties in the analysis.
This reaction has the largest cross section for detection but is only weakly directional. The “elastic scattering” (ES) reaction
\[ \nu + e \rightarrow \nu + e \]
has opposite properties in this respect: We can identify the direction of the neutrino source, just as in ordinary astronomy, thanks to the fact that the electrons are scattered almost in the same direction of the neutrinos. Of course, the limited data set does not permit a very precise identification; though, we expect to be able to locate a supernova at the border of the Milky Way with a precision of some degrees.\(^3\) For details and references, see [11] and [3].

### 2.5. Search for gravity wave burst

There are various moments when gravity waves (GW) could be emitted during a core collapse. One possibility is during the formation of the neutron star, when the inner core reaches the highest densities and bounces. Several simulations find that this moment is associated with a GW burst emission, even if, sometimes, this emission is found to be rather weak. The process of emission is pretty fast, lasting only some tens of milliseconds, and should almost coincide with the beginning of neutrino emission. The question that we would like to consider is the following: how effective are neutrinos to indicate the moment of the emission?\(^4\) The time of the bounce, when a GW burst emission should occur, can be obtained from:

\[ T_{\text{bounce}} = T_{1st} - t_{\text{mass}} - t_{\text{GW}} - t_{\text{fly}} - t_{\text{resp}} \]  

where the first term in the right hand side is the time of the first neutrino event and:

(i) the delay \( t_{\text{mass}} \) due to the mass is small, if the cosmological limit of about 1 eV applies;
(ii) the intrinsic delay \( t_{\text{GW}} \) is just 1.5-4.5 ms;
(iii) the error on the geometrical delay \( t_{\text{fly}} \) is below 5 ms using ES events;
(iv) the most relevant term is \( t_{\text{resp}} \), the delay between the first neutrino and the first event.

\(^3\) In order to improve the identification of the ES signal, one could impose the correlation of the observed directions of arrival with the galactic plane. Moreover, it is possible to adopt some criteria to increase the purity of the ES sample: e.g., kinematics imposes that the energy is shared between the final-state electron and neutrino, thus reducing the observable energy. Also, according to recent simulations, the initial ES emission has a very high average energy, which would be in agreement with the first event observed by Kamiokande-II.

\(^4\) The traditional attitude was “the GW burst will give the \( t_0 \) of the neutrino emission”; the new attitude is motivated by the expectation that we will be able to observe neutrinos with high statistics. There is no real contradiction between these views; indeed it would be important to know “\( t_0 \)” independently from the neutrinos, e.g., to investigate neutrino masses. Moreover, considering SN1987A findings with open mind, we should not neglect the possibility of major surprises, also thanks to the new types of GW detectors [13].
The last quantity can be obtained by fitting the neutrino data. This is where the parameterized model enters [3]. Considering, as an example, Super-Kamiokande we find this quantity with an error less than 10 ms. In [12], IceCUBE is considered using a much simpler fit to the simulated data and yields a similar result. Finally, by summing the errors, we conclude that we can estimate the time of the bounce with a remarkable precision:

$$\delta T_{\text{bounce}} = \sqrt{\delta t_{\text{mass}}^2 + \delta t_{\text{GW}}^2 + \delta t_{\text{fly}}^2 + \delta t_{\text{resp}}^2} \approx 15 \text{ ms}$$

This accuracy in the measurement of the time is well-matched to the duration of the GW burst, $\approx 30$ ms. Thus, neutrino observatories should provide gravity wave observatories, such as Virgo and LIGO, with a good trigger to search for a GW burst.

2.6. Diffuse supernova neutrino background

The diffuse supernova neutrino background (DSNB), or relic supernova neutrinos, is the result of the cosmic supernova emissions cumulated in the course of time. In principle this is visible in an energy window approximatively above $E_{\text{th}} = 20$ MeV (or 10 MeV, depending on detector capabilities). Unfortunately, DSNB gives a feeble signal; but, in view of its interest in astrophysics and particle physics, it is the target of experimental search. The best limit, to date, is due to SK [14]. There are interesting prospects to proceed further in the experimental investigation, e.g., improving the tools of analysis or adding Gadolinium, which corresponds to the entry denoted by SK+ in Table 1. Assuming that the SN1987A was representative of the standard electron antineutrino emission, ref. [4] has used our parameterized model to predict the expected DSNB signal and the error-bar in the prediction (i.e., the uncertainty). The results of the analysis are given in Table 1. It is reassuring to note that a completely different procedure [16], based on a comparison of different theoretical models for the emission, yields very similar results for the error-bar.

3. Summary and discussion

We discussed a parameterized model for the analysis of supernova neutrinos [1, 3, 10], which elaborates on the earlier proposal of Loredo & Lamb [6]. We argued that our model is adequate for the analysis of SN1987A observations and it is significantly superior to those used in previous

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5 The number of DSNB events per year is roughly the same as those from a supernova as SN1987A, exploded 6 times farther from us and detected with an efficiency $\epsilon(E) = E/E_{\text{th}} - 1$ for $E > E_{\text{th}}$ [4].
analyses, as those described in [17] or those presented in [18]. We illustrated its usefulness, by showing several applications in particle physics and astrophysics. We know that this model could be still improved—or even corrected, if necessary—with the contribution of astrophysicists. Such a step will be most probably necessary to interpret the result of a future observation, but it is not excluded that it could be useful also to understand even better the existing ones. (This statement is independent from the dubious aspects of SN1987A, see [9] for a review; in the dry language of statistics, we are just stressing the need to correctly formulate what is the null-hypothesis to interpret the data collected by Kamiokande-II, IMB and Baksan.)

However, the problem of designing parameterized models to describe neutrino emission is not felt as urgent among theorists interested in supernovae: astrophysicists concentrate towards understanding the explosion (see e.g. [20]), whereas, particle physicists concentrate on the oscillations (see e.g. [21, 18]). In the field of supernova neutrinos, experimentalists and theorists are working independently as happens in many other fields in physics; but it is curious that there is so little interaction among theorists with different expertises, though they are interested in understanding the same thing.

A historical account permits us to see the dangers of this attitude, see also [18]. Just after SN1987A, the average energy of the observed events—especially those of Kamiokande-II and Baksan—were generally considered below the expectations, see e.g., [17, 22] and the lower panel of Fig. 1. This opinion contributed to a diffuse feeling that SN1987A could be non-standard [18]. It also stimulated a long discussion on oscillations (see [9] for a critical review) eventually terminated when the average energies of the non-electronic antineutrinos were found to be lower than previously expected [23]. Recently, also the average energies of electron antineutrinos started to diminish significantly, see [20, 18]. This implies that, after 20 years, the theory begins to match the only observation we have. In our view, this story also witnesses that we need more theoretical work on the neutrino fluxes, devoted to assess the theoretical errors in the predictions, and to identify the generic features of supernova neutrino emission.

We close recalling that many supernova neutrino detectors are operational and more will come [24]. They should be considered as telescopes, aimed at observing one of the most important chain of events in astronomy: the gravitational collapse of a stellar core, most likely followed by an explosion and by the formation of a compact star. Its observation by means of neutrinos, and possibly of gravitational waves, will permit us to progress greatly in astrophysics, nuclear

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6 The comparison with the results of Loredo & Lamb is discussed in [1] and [19]. Despite a large number of differences in the assumptions and in the model, we subscribe their main conclusion: the data of Kamiokande-II, IMB and Baksan suggest that the initial luminosity was much larger than the average one.
Figure 9. Illustration of how an excessive confidence or diffidence in the theory may paradoxically lead to the same result, namely, of stopping any further investigation of the observations.

physics and particle physics. A reliable, complete and flexible model for neutrino emission would be a precious tool to examine the expectations and to plan the next steps.

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