SN1987A and the properties of the neutrino burst

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We reanalyze the neutrino events from SN1987A in IMB and Kamiokande-II (KII) detectors, and compare them with the expectations from simple theoretical models of the neutrino emission. In both detectors the angular distributions are peaked in the forward direction, and the average cosines are 2 sigma above the expected values. Furthermore, the average energy in KII is low if compared with the expectations; but, as we show, the assumption that a few (probably one) events at KII have been caused by elastic scattering is not in contrast with the "standard" picture of the collapse and yields more satisfactory distributions in angle and (marginally) in energy. The observations give useful information on the astrophysical parameters of the collapse. We find that the mean energy of electron antineutrinos is $\langle E\rangle = 12-15$ MeV, the total energy radiated around $(2-5)\times 10^{53}$ erg, and there is a hint for a relatively large radiation of nonelectronic neutrino species. These properties of the neutrino burst are not in disagreement with those suggested by the current theoretical paradigm, but the data leave wide space to nonstandard pictures, especially when neutrino oscillations are included.

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I. MOTIVATIONS AND CONTEXT

The detection of neutrinos from SN1987A marked the beginning of (extra)galactic neutrino astronomy [1–6] (see also [7–9] for comprehensive reviews of SN1987A observations). The observations of Kamiokande have been mentioned and recognized in the 2002 Nobel prize for Physics. However, when one studies the data, one meets a number of surprising, unexpected or even puzzling features. Let us recall which are the main ones.

(1) The angular distributions of the events seen at Kamiokande-II (KII) and at Irvine-Michigan-Brookhaven (IMB) are more forward-directed than expected, for instance, the average cosines of the polar angles are $\langle \cos\theta^{\rm KII}\rangle \sim 0.3$ and $\langle \cos\theta^{\rm IMB}\rangle \sim 0.5$.

(2) Also, the energy distribution of these two detectors seems not to be perfectly in agreement. In particular, $\langle E_{vis}^{\rm KII}\rangle$ is half of $\langle E_{vis}^{\rm IMB}\rangle$ (about 30 MeV), that is, a very marked difference even taking into account the different performances of the detectors.

(3) Even the time distribution of the events in the two detectors looks to be different. However, when data are combined the distribution in time does not contradict the current picture of a "delayed explosion" according to Lamb and Loredo analysis [10].

(4) The Mont Blanc events [6] occurred 4.5 hours before the other ones. This led some Authors to consider two-stage scenarios for the collapse [11,12].

In this work, we will focus on the discussion of the first issue and will stress the connections with the second one. More in general, we believe that these data raise several important questions that deserve attention, for instance: How likely is it that the anomalies in the distributions are due to fluctuations, and in particular, how significant is the hint for some feature in the angular distributions? What can we learn (and what we can exclude) on the nature and the properties of the stellar collapse from these observations?

A number of recent facts, beside the general considerations exposed above, testify the interest in having a fresh look at the SN1987A data: (a) several experimental evidences (in particular [13–15]) strongly suggest that SN1987A neutrinos oscillated in flavor; (b) the expectations of the emitted neutrino radiation has been recently reconsidered [16], suggesting a new paradigm for the distribution of neutrinos and antineutrinos; (c) there have been improvements in the description of the cross section of

$$\overline{\nu}_e p \to e^+ n, \quad \text{IBD reaction (from ``inverse beta decay'')} \tag{1}$$

in the energy range relevant for supernova neutrinos [17,18]. Moreover, it is correct to recall that we do not understand yet the theory of core collapse supernovae, and therefore one could argue that we miss the most important ingredient for a proper interpretation. However, a reasonable working hypothesis is to describe the emitted neutrino radiation by a model with few parameters, suggested by the "delayed explosion" scenario proposed in [19], see [20] for a recent report. This is the point of view we will adopt in a large part of the present investigation.

We will describe and motivate in the rest of this section what we assume (based on expectations and observations) as a reference neutrino flux. We will discuss a standard (but updated) comparison of observations and expectations in Sec. II, based on IBD hypothesis (see below), that will per-

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mit to further define the parameters of the model of neutrino emission. In Sec. III, we will use this model to analyze the angular features of the spectra, state the situation quantitatively, and consider a few alternatives to improve the agreement with the data. We summarize the results obtained in the last section.

A. Neutrino flux

A simple model of the fluxes [16] of supernova neutrinos attributes the following spectra (with three different average energies E_0) to any species ν_e, $\nu_{\bar{e}}$ or ν_x–x being any among muon and tau (anti)neutrinos:

$$\Phi_i(E)=\frac{\mathcal{E}_i}{4\pi D^2}\frac{N}{E_0^2}z^{\alpha}e^{-(\alpha+1)z},\quad z=E/E_0, \tag{2}$$

where $i=e,\bar{e},x$ and $N=(\alpha+1)^{\alpha+1}/\Gamma(\alpha+1)$. The total fluence at the detector is $\int E\Phi_i(E)dE=\mathcal{E}_i/4\pi D^2$, thus $\mathcal{E}_i$ is the amount of irradiated energy in the neutrino species i (the flux is supposed to be emitted isotropically) and D the SN-detector distance. Numerical calculations find that the time integrated flux Φ, usually called "fluence," is rather well described by this ansatz; in particular, the deviations from a thermal shape are not large, and can be described as we do here by setting $\alpha=3$ for all neutrino species ($\alpha=2$ amounts to a Maxwell-Boltzmann distribution). Finally, the meaning of E_0 is just the average energy of the species considered (we will take $E_0=\langle E_{\bar{e}}\rangle$ in the following).

The total energy emitted in neutrinos can be estimated by simple considerations. In fact, the total gravitational energy irradiated is $\mathcal{E}_B\sim 3G_N M_{ns}^2/5R_{ns}$, and using for the neutron star a mass of $M_{ns}=(1–2)M_{\odot}$ and a radius of $R_{ns}=20$ km $(M_{\odot}/M_{ns})^{1/3}$, we get $\mathcal{E}_B\sim(1–5)\times 10^{53}$ erg. The amount of energy that goes in the specific flavors is uncertain. Since $\mathcal{E}_e$ is not very important for the observed signal (see below), we will always set $\mathcal{E}_e=\mathcal{E}_{\bar{e}}$, unless stated otherwise. Instead, we will distinguish three cases for the emitted energy $\mathcal{E}_x$ (assumed to be equal for ν_μ, $\nu_{\bar{\mu}}$, ν_τ and $\nu_{\bar{\tau}}$, so that $\mathcal{E}_B=\mathcal{E}_e+\mathcal{E}_{\bar{e}}+4\mathcal{E}_x$) that, as we will see, plays a more important role:

(1) $\mathcal{E}_x=\mathcal{E}_{\bar{e}}$: This is the so-called "equipartition," often adopted in theoretical analyses.
(2) $\mathcal{E}_x=\mathcal{E}_{\bar{e}}/2$: This is the case when a large part of the radiation goes in electron neutrinos.
(3) $\mathcal{E}_x=2\mathcal{E}_{\bar{e}}$: Finally, in this case most of the radiation goes in muon or tau neutrinos.

The average energies are important parameters. $\langle E_x\rangle$ is greater than $\langle E_{\bar{e}}\rangle$, but the amount of hierarchy found in modern calculations is not very large. A typical ratio is in the range 1–1.2. In the following, we will assume (unless stated otherwise) $\langle E_x\rangle=1.1\langle E_{\bar{e}}\rangle$. The average energy of the electron neutrinos $\langle E_e\rangle$ instead is not of crucial importance for the observed signal. It can be evaluated by prescribing a condition on the emitted lepton number $\Delta L_e=N(\nu_e)-N(\overline{\nu}_e)$ where $N(\nu_e)=\mathcal{E}_e/\langle E_e\rangle$ and similarly for the antineutrinos; we will assume that the electrons contained in one solar mass of iron are converted in neutrinos.

The crucial parameters needed to describe the neutrino signal are the antineutrino average energy,

$$E_0\equiv\langle E_{\bar{e}}\rangle=12–18\ \text{MeV}\quad(\text{expected}) \tag{3}$$

and the total energy irradiated in antineutrinos

$$\mathcal{E}_{\bar{e}}=(2–10)\times 10^{52}\ \text{erg}\quad(\text{expected}). \tag{4}$$

Both of them have considerable uncertainties, especially the second one. For this reason, the uncertainty in the distance of the supernova is usually considered unimportant; here, we will assume $D=52$ kpc, and discuss this point later.

B. Impact of neutrino oscillations

Motivated by the solar and atmospheric results, we assume that the three neutrinos ν_e, ν_μ and ν_τ have mass and mix among them. Following simple minded theoretical expectations, we will further assume in most of this paper that the heaviest state is separated by $\Delta m_{31}^2\approx 2.5\times 10^{-3}$ eV^2 from the other two, whose splitting is $\Delta m_{21}^2\approx 7\times 10^{-5}$ eV^2. The known mixing angles are $\theta_{23}\approx 45°$, $\theta_{12}\approx 34°$, while θ_{13} is unknown but presumably it is not very small (we take $\approx 6°$ when needed, but its impact on the oscillations is usually of minor importance). With these parameters, the emitted fluxes from SN1987A, described in Sec. I A, should be modified to account for the MSW effect in the star [21–25] (among first papers on the topic, we recall [26–30]):

$$\Phi_e\to P_{ee}\Phi_e+(1-P_{ee})\Phi_x,$$

$$\Phi_{\bar{e}}\to P_{\bar{e}\bar{e}}\Phi_{\bar{e}}+(1-P_{\bar{e}\bar{e}})\Phi_x, \tag{5}$$

where the two probabilities of survival are $P_{\bar{e}\bar{e}}=\cos^2\theta_{12}\approx 0.7$ and $P_{ee}=\sin^2\theta_{13}\approx 0$. (We will discuss other possibilities, as a very small θ_{13}, or an "inverted" mass hierarchy, in Sec. III D.) The MSW effect of the Earth modifies $P_{\bar{e}\bar{e}}$ by a minor amount [31].

Two remarks are in order: (1) It is difficult to conceive that oscillations did not occur; for instance, the MSW effect related to solar Δm^2 happened unless there was a drastic modification of the mantle of the star for densities around 10 gr/cc, which seems unlikely. (2) The effects for $\overline{\nu}_e$ are of about 30%, while those for ν_e can be much larger; for instance, in the framework described above, the observed ν_e flux corresponds almost exclusively to emitted ν_μ or ν_τ. This is the reason why $\mathcal{E}_x$ has an important role for the signal seen in terrestrial detectors.

II. THE IBD HYPOTHESIS

In the model previously described and with the expected values of the parameters, it is a fact that most of the events expected at KII, IMB and Baksan are due to the inverse beta decay process. This is the reason why several analyses adopted the simplifying hypothesis that *all* events come from IBD (see e.g. [32]). We begin by repeating such a more-or-less standard analysis, with three specific aims: (1) stressing

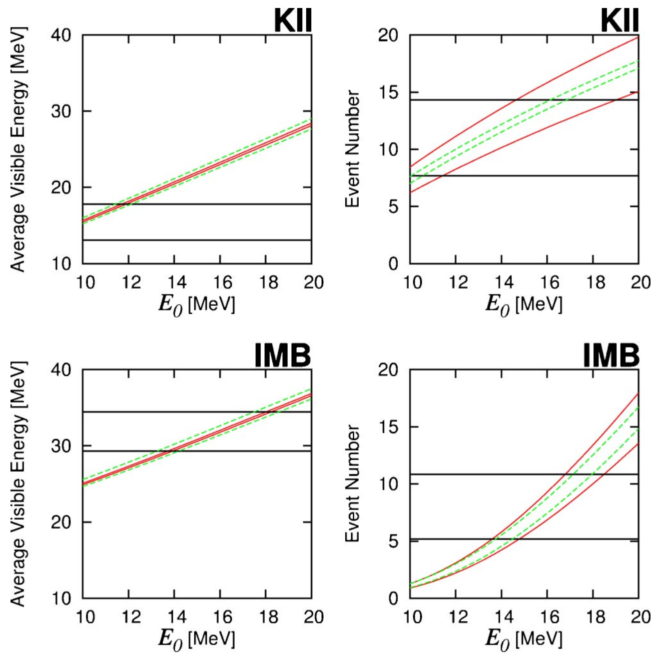

FIG. 1. Comparison of observations (horizontal strips) and expectations calculated in the IBD hypothesis. The left panels show the average visible energy, the right ones the number of events. The upper panels are for KII, the lower ones for IMB. For any panel, we show 4 expectations curves. The continuous (red) ones correspond to a variation of the theoretical parameter $\mathcal{E}_x$ (=energy radiated in $\overline{\nu}_{\mu,\tau}$) in the range $(2-6)\times 10^{52}$ erg. The dashed ones (green) correspond to a variation of the theoretical parameter $\langle E_x \rangle$ (=average energy of the emitted ν_μ, $\nu_{\bar{\mu}}$, ν_τ and $\nu_{\bar{\tau}}$) in the range (1–1.2) $\times E_0$.

observables with a clear physical meaning (rather than attempting a global analysis of the data); (2) discussing how the data of the three experiments fit in the theoretical picture; (3) getting more specific values of the parameters of neutrino emission. The calculations of the expectations are quite simple. In a detector with N_p protons and with detection efficiency $\epsilon(E)$ (function of the positron energy) one integrates the differential event rate

$$\frac{dN_{ibd}}{dE_\nu dE} = N_p \epsilon(E) \Phi_{\bar{e}}(E_\nu) \frac{d\sigma_{ibd}}{dE}(E_\nu, E) \tag{6}$$

over the allowed range, obtaining the value of the observable of interest—e.g., the visible energy in Čerenkov detectors $E_{vis}=E$, while in scintillators, there is an additional contribution of $2m_e \sim 1$ MeV from positron annihilation [note that the fluence Φ in Eq. (6) should be thought as differential in the transversal surface *and* in E_ν]. In Figs. 1 and 2, we show the value of two simple but important observables: the mean energy and the number of events. In these figures, the effect of varying $\langle E_{\bar{e}} \rangle$, $\langle E_x \rangle$ and $\mathcal{E}_x$ in certain ranges are illustrated. For IMB, we reduced the expected number of events by 13% to take into account the dead-time occurred during the detection of the burst [2]. Let us comment on the results in some detail.

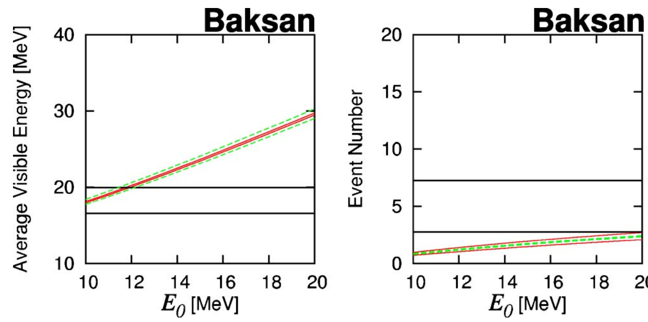

FIG. 2. Same as Fig. 1 for Baksan.

(*a*) *Average visible energy*. This observable has the advantage of being independent of the total energy emitted, and of having relatively small errors:

$$\delta E_{vis} = \sqrt{\frac{\langle E_{vis}^2 \rangle - \langle E_{vis} \rangle^2}{N}} = \begin{cases} 2.4 \text{ MeV at KII,} \\ 2.6 \text{ MeV at IMB,} \\ 1.7 \text{ MeV at Baksan.} \end{cases} \tag{7}$$

In the IBD hypothesis E_{vis} is the energy released by the positron. While IMB points to a range of values nicely consistent with expectations, compare with Eq. (3), the data of KII and Baksan point to somewhat lower values. Note that we discard from the analysis the sixth event of KII, since it has $N_{hit}=16$, below the threshold $N_{hit}=20$ of software analysis [4]. Indeed, it should be remarked that the lower energy events at KII are those for which pollution from background is more likely; in particular, in the window of 12 sec in which the supernova neutrinos have been detected, we estimate an average of about 2 background events [4]. The situation at Baksan is a bit different, since also high energy events could be contaminated by the background [10]; however, the lowest energy event has 12.0 ± 2.4 MeV that is not far from the threshold of 10 MeV [5]. Instead, due to the high threshold for data taking, IMB can be considered as background free. From Figs. 1 and 2, one sees that the impact of a variation of $\langle E_x \rangle$ and $\mathcal{E}_x$ on the expectation for the average visible energy is not large.

(*b*) *Number of events*. The observables $N^{\mathrm{KII}}=11$, $N^{\mathrm{IMB}}=8$ and $N^{\mathrm{Baksan}}=5$ have large Poisson errors, but permit to estimate the energy emitted from the supernova (whereas the previous observable is not useful for this purpose). In the plots on the right of Figs. 1 and 2, the energy emitted in any species of neutrino is chosen by default to be 4×10^{52} erg. The agreement with the expectations is good for KII and IMB. The expected number of events at Baksan is low [33] up to the point that the agreement is poor even ascribing one of the 5 events to the background. To explain N^{Baksan} without resorting to fluctuations, we would need to assume a very large value $\mathcal{E}_{\bar{e}} \sim 1\times 10^{53}$ erg, but in this way we would lose the agreement with IMB and Kamiokande II completely. The impact of a variation of $\mathcal{E}_x$ is not fully negligible for all data sets, but this is easy to understand and to keep in account: Indeed, the signal scales roughly as $0.7\mathcal{E}_{\bar{e}} + 0.3\mathcal{E}_x$, thus a variation in $\mathcal{E}_x$ can be well "simulated" by a variation of the total emitted energy.

(*c*) *Summary*. Using these results as a guide, we further specify the parameters of the model and assume

$$E_0 \equiv \langle E_{\bar{\nu}_e} \rangle = 14 \text{ MeV}, \quad \mathcal{E}_{\bar{\nu}_e} = 4 \times 10^{52} \text{ erg}. \tag{8}$$

These values should be thought of as compromises between contrasting needs. In fact, various indications pull in different directions: (i) KII and Baksan energy spectra would prefer lower values of E_0; IMB instead would prefer slightly larger values. The observed visible energy (averaged over all experiments) is 8% below the value expect from Eq. (8). When we take into account the expectations, Eq. (4), we would prefer larger values of E_0. (ii) The values in Eq. (8) fit well IMB and KII data set. The total number of expected events is 19.1, and to better account for the unexpectedly large number of events seen at Baksan we should increase $\mathcal{E}_{\bar{\nu}_e}$ by about 20%. (iii) In order to reproduce the number of events of IMB and KII at central values, we would need $E_0 \sim 18$ MeV and $\mathcal{E}_{\bar{\nu}_e} = 3 \times 10^{52}$ erg (but these values contradict the average energies dramatically). (iv) The angular distributions discussed below would suggest to have an E_0 as high as possible.

These considerations show that there is a certain degree of tension between the various pieces of data and also with the expectations. Anyhow, assuming that the IBD hypothesis is correct, the models with values in the ranges $E_0 = (12\text{–}15)$ MeV and $\mathcal{E}_{\bar{\nu}_e} = (3\text{–}6) \times 10^{52}$ erg do not contradict the data, and these ranges are certainly within the theoretical uncertainties. The specific values of Eq. (8), however, are not critical for the subsequent analysis.

Let us conclude stressing a point that will be touched again in the following: Within the "standard" model of the collapse and with the parameters of Eq. (8), the observed average visible energy at KII looks a bit small.

III. WHAT IS THE MEANING OF THE FORWARD EVENTS?

In this section we study the angular distribution of the events from SN1987A. Thus, we select the events from the two water Čerenkov detectors operative at that time, and use the data from [2] for IMB, and those from [4] for KII. The data of Baksan do not carry angular information and, therefore, are not taken into account in the following. Both angular distributions in KII and IMB are rather forward-directed. To state this more precisely, we calculate the average angles: $\langle \cos \theta^{\mathrm{KII}} \rangle = 0.29 \pm 0.27$ and $\langle \cos \theta^{\mathrm{IMB}} \rangle = 0.48 \pm 0.34$. Here we have used a weighted average and the corresponding standard deviation errors.

(*a*) *Beyond the IBD hypothesis*. We can compare the data with the expectations from the IBD hypothesis. Using parametrized angular distributions

$$dN/dz = a_0 + a_1 z + a_2 z^2,$$

where

$$z = \cos\theta \quad \text{and} \quad a_i \quad \text{as in Table I} \tag{9}$$

TABLE I. Approximate coefficients of the angular distributions for IBD using Eq. (8).

	a_0	a_1	a_2
KII	0.499	0.030	0.003
IMB	0.495	0.104	0.014
IMB with bias	0.492	0.154	0.024

obtained from [18] we find that both central values are above the expected ones: 2.3σ for IMB and 1.7σ for KII. This conclusion is in agreement with [17]. In this study, we adopt the model defined in the previous section with the parameters of Eq. (8). We checked that a variation of these parameters is not crucial for the conclusions, while $\mathcal{E}_x$ is of greater importance. It is simple to explain the reason: The only type of events that is strongly forward (and thus is able to affect the angular shape of the distribution) are those from

$$\nu_i e \to \nu_i e, \quad \text{ES reaction (from "elastic scattering")}, \qquad i = e, \bar{e}, x. \tag{10}$$

This reaction receives contributions from all neutrino types, and ν_e gives the largest one. But due to oscillations, Eq. (5), the observed ν_e flux is originally due to ν_x; this implies the relevance of $\mathcal{E}_x$, namely, the energy emitted in $\nu_{\mu,\tau}$. The hypothesis that one or more forward peaked elastic scattering events could be present in the data samples of IMB and KII has been already considered in the past, see e.g. [7,34–38]. In this analysis, however, we update the angular distributions for IBD events and the model for neutrino emission, compare different statistical inferences and include oscillations with recently measured parameters.

(*b*) *Instrumental effects*. A point to take into account is that the angular distributions (and in particular the one of ES) are modified in an important manner by instrumental effects. This is due to multiple scattering and limited angular resolution of the detectors, and it is called "smearing" of the angular distributions. In order to account for this, we use the following distribution [39]:

$$\rho_{sm}(\cos\theta_s)\, d\cos\theta_s = N e^{-\theta_s^2/2\sigma_s^2} \sin\theta_s\, d\theta_s, \tag{11}$$

where θ_s is the angle of smearing and σ_s is a measure of the effect; N in Eq. (11) is just a normalization factor. For KII, where the smearing is slightly more important, we choose σ_s in such a way that the mean angle $\overline{\theta}$ from Eq. (11) corresponds to the mean error $\delta\theta$ determined from the data [4]. For the whole set of data we have $\delta\theta \sim 25°$, while considering only data with $\theta \leqslant 30°$ we find $\delta\theta \sim 18°$. As a consequence we decide to study the two cases, when $\sigma_s = 15°$ and $\sigma_s = 20°$, for which $\overline{\theta} \sim 18°$ and $\sim 25°$, respectively. Based on similar considerations [2] we set $\sigma_s = 16°$ in IMB. Using Eq. (11) and ρ_{es}, e.g., from [42] we can determine the reconstructed angular distribution as follows:

$$\rho_{es}^{rec}(\mathbf{n}\cdot\mathbf{m}) = \int d^2\mathbf{p}\, \rho_{sm}(\mathbf{m}\cdot\mathbf{p})\, \rho_{es}(\mathbf{n}\cdot\mathbf{p}), \tag{12}$$

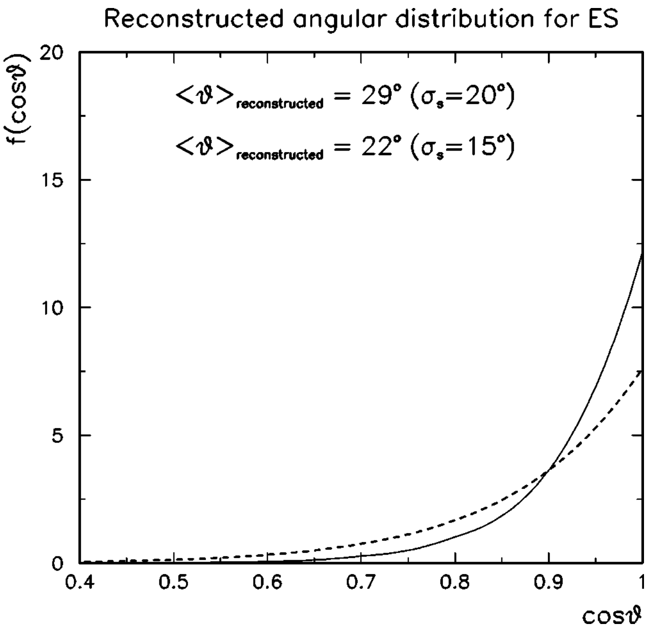

FIG. 3. Reconstructed angular distribution for elastic scattering events in KII.

where **n**, **m** and **p** are unitary vectors for the SN, the reconstructed and the emitted direction respectively, $\mathbf{n}\cdot\mathbf{m}=\cos\theta$, $\mathbf{m}\cdot\mathbf{p}=\cos\theta_s$, $\mathbf{n}\cdot\mathbf{p}=\cos\theta\cos\theta_s+\sin\theta\sin\theta_s\cos\phi_s$, and $d^2\mathbf{p}=d\cos\theta_s d\phi_s/4\pi$ is an element of solid angle from which the signal receives a contribution. The reconstructed distributions we obtain for KII are plotted in Fig. 3. Since the angular distribution ρ_{es} of ES is rather narrow (especially when taking into account detector efficiencies) the reconstructed angular distribution of ES is mostly dictated by instrumental effects.

A. Angular distribution of IMB

The normalized positron angular distribution for inverse beta decay is usually taken in the simple approximation $dN/d\cos\theta=0.5+a\cos\theta$; in particular, in the IMB report [2] it is assumed $a\sim0.07$. In the same paper it is pointed out that to account for the experimental polar-angle efficiency, one can introduce a 10% angular bias. This is equivalent to replace $dN/d\cos\theta\rightarrow(1+0.1\cos\theta)dN/d\cos\theta$. We use the improved cross section for IBD from [18] to determine the parameters a_i $(i=0,1,2)$ in Table I, that enter in the angular distribution of Eq. (9). We notice that a_i's in Table I do not depend significantly on the assumed mean energy E_0.

We have used Eq. (9) to test the hypothesis the data from IMB come from IBD events, employing the Smirnov–Cramer–Von Mises (SCVM) statistics [40]. As shown in the left panel of Fig. 4 the goodness of fit (g.o.f.) for this hypothesis is equal to 6.4%. The improved IBD angular distribution changes the previous result (4.5% [2]) by only a small amount due to the poor statistics. However, the importance of using the improved angular distribution is evident when we compare the old significance without angular bias with the new one, since 1.5% [2] increases to 4.2%. In the same figure we show the cumulative distribution in the hypothesis of having 1 ES event in IMB.

To study the possibility to have a small contribution of elastic scattering (ES) events in IMB and later in KII we have exploited the maximum likelihood (ML) method [41]. In this framework the likelihood function is written:

$$L\left(\frac{n}{n_{obs}}\right)=\prod_{i=1}^{n_{obs}}\rho\left(\cos\theta_i\,;\frac{n}{n_{obs}}\right),\qquad(13)$$

where n/n_{obs} is the parameter which measures the fraction of ES events, n_{obs} being the total number of experimentally observed events for the SN. The angular distribution $\rho(\cos\theta_i;n/n_{obs})$ can be written as $\rho(\cos\theta;n/n_{obs})=(n/n_{obs})\rho_{es}^{rec}(\cos\theta)+(1-n/n_{obs})\rho_{ibd}(\cos\theta)$, where ρ_{es}^{rec} and ρ_{ibd} are the angular distributions for ES and IBD, respectively. It turns out that in IMB the best-fit is found for $n/n_{obs}=0$. The effect of the smearing is not particularly important in IMB. In order to determine an upper limit on the likelihood parameter we have built a posterior probability distribution function (p.d.f.) by normalizing the likelihood function and considering a uniform prior p.d.f. which is equal to one for $n/n_{obs}\geqslant0$, zero elsewhere. It turns out that $n/n_{obs}<0.12$ at 68.3% C.L., namely the IMB angular distribution admits one ES event at most.

B. Angular distribution of KII

As stated above we consider $n_{obs}=11$ out of 12 candidate events [4] and assume the event number 6 due to background. In Fig. 3 we show the reconstructed angular distributions for the cases $\sigma_s=15°$ and $\sigma_s=20°$. The smearing effect in KII plays an important role (without smearing, $\langle\theta\rangle=10°$). Using the ML from Eq. (13) we have computed the likelihood ratio $L(n/n_{obs})/L_{max}$ with $n=0,1,2,3$ to quantify the probability to have zero, one or more ES events on the basis of the angular distribution. In Fig. 5 we show the normalized ML function against n/n_{obs}. Minimizing $-\ln L(n/n_{obs})$ the best-fit is found for $n/n_{obs}=0.35\pm0.20(1\sigma)$ for $\sigma_s=20°$ and $n/n_{obs}=0.23^{+0.21}_{-0.18}(1\sigma)$ for $\sigma_s=15°$. So, the ML test suggests that a few ES events are present in the KII data set.

As for IMB we have exploited the SCVM test (see Fig. 4). Moreover, we have worked out the probability to have $n=0,1,2,3$ ES scattering events using the expectations based on the SN model described above. For this latter case we have written the probability to have n ES events out of a total of $n_{obs}=11$ as the product of two Poisson distributions, that is equal to

$$P(n)=\frac{e^{-n_{exp}}}{n_{obs}!}n_{exp}^{\,n_{obs}}\times B_p(n,n_{obs}),\qquad(14)$$

where the first factor is a Poisson distribution with a mean value $n_{exp}=n_{es}+n_{ibd}$ and the second one a binomial distribution with a trial probability $p=n_{es}/n_{exp}\sim0.03$; for instance, for the equipartition scenario we found 11.9 IBD events and 0.39 ES events. (Incidentally, one should notice that the calculation of the ES number of events is *very* sensitive to the experimental efficiency at the lowest measurable

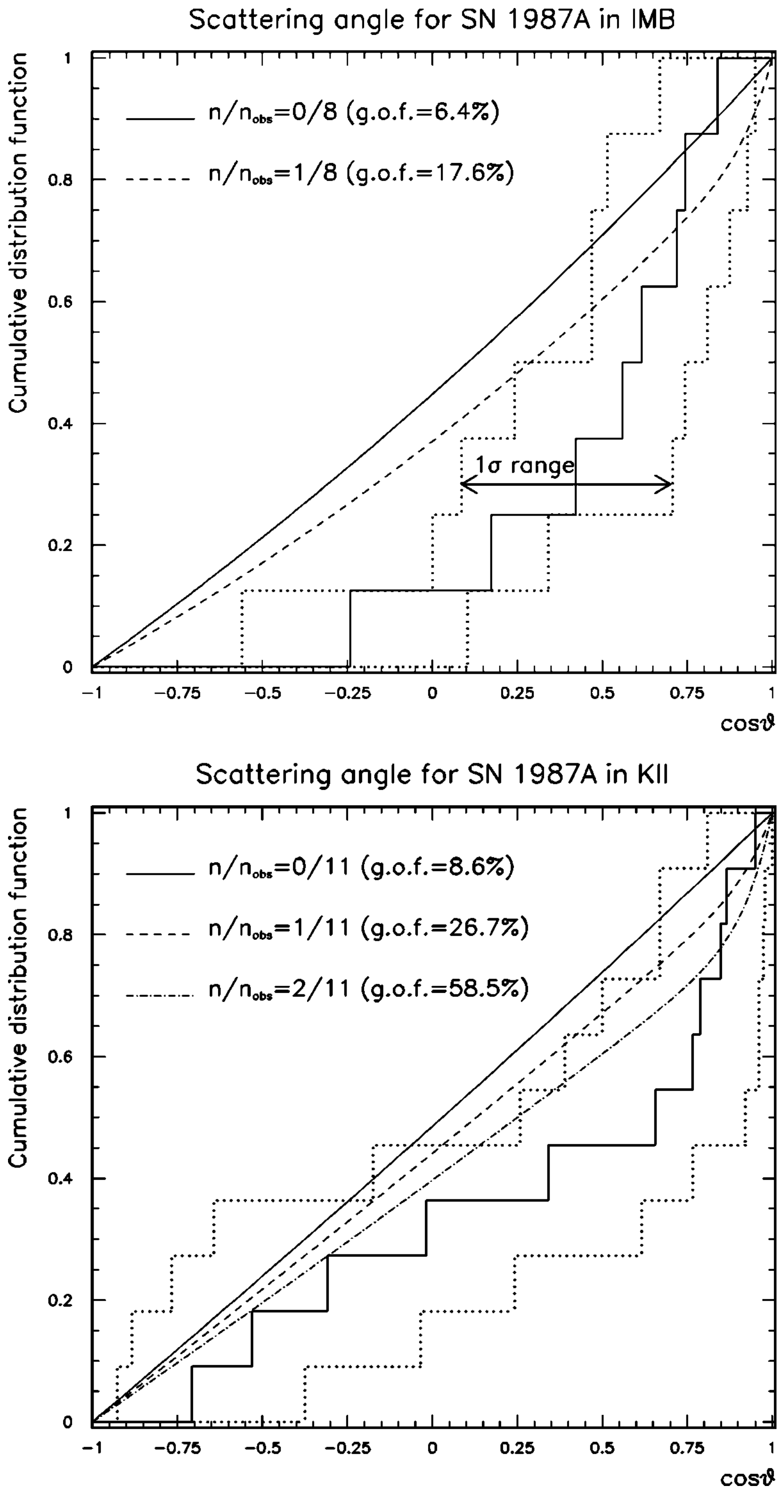

FIG. 4. Theoretical and experimental angular distributions in IMB (upper panel) and KII (lower panel). The 1 sigma range and the goodness of fit figures are also shown. For KII, we adopt $\sigma_s = 15°$.

energies). In Table II we summarize our results. Similar calculations were made for IMB.

C. Summary for the "standard" scenario and remarks

It is instructive to compare here the outcomes of the two statistical tests we used: the Smirnov–Cramer–Von Mises (SCVM) and the maximum likelihood (ML). The comparison with the data follows completely different strategies: the ML method is "local" in the sense that it profits of events that fall under the ES bell (of Fig. 3), while the SCVM is "global" in the sense that it tries to minimize the maximal distance between the theoretical curve and the observed one. For IMB the SVCM test suggests more elastic scattering events than the ML test does (the reason can be understood from the right-most part of Fig. 4a: the most forward event has polar angle $33° \pm 15°$, thus its central value is not forward enough to suggest an ES event). Instead, for KII the two tests give very similar indications.

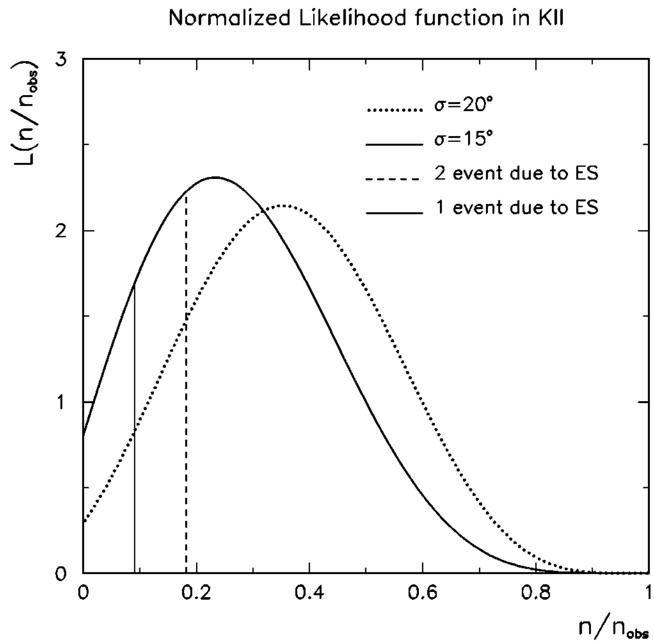

FIG. 5. Normalized likelihood function versus the fraction of expected ES events in KII. For the smearing of the angular distribution we show the cases $\sigma=20°$ and $\sigma=15°$.

Next, we take into account also the theoretical expectation on the number of ES events, and use it together with the results from the angular distribution. We combined the information from the SN model and that from the SCVM analysis in Table II, multiplying the probabilities and normalizing the resulting distribution to one. The results for KII are shown in Table III, and the combined probabilities are given for the case $\sigma=20°$ (the case $\sigma=15°$ gives about the same result). In particular, from Table III we see that one ES in KII can be accepted at about the same level we could accept zero events. Moreover, even the probability to have two ES events is indeed not negligible. Repeating the exercise for IMB, we find that at ''equipartition'' ($\mathcal{E}_{\bar{e}}=\mathcal{E}_x$) the combined probability to have zero (one) events is 80% (19.9%).

Some remarks are in order.

(1) The data of KII show that the most directional events have energies above 20 MeV. Taking this experimental fact into account, we checked the probability to have events with $E_e \geqslant 20$ MeV for the three scenarios of SN considered. As shown in Fig. 6 this probability is about 16%. So, it seems not unlikely [43] from this point of view to have measured ES events with energies above 20 MeV.

(2) The presence of one or more ES events in KII dataset goes in the right direction to explain the disagreement between IMB and KII average energies. However the effect is admittedly small, since for instance 1 ES event that produces 20 MeV of observable energy originates from a neutrino with larger energy, but just of 5 MeV on average. If the number of ES events in KII is larger, this could become more important.

TABLE II. Expected probabilities that zero, one or more events in KII are due to ES, for $\sigma_s=15°$ (upper part) and $\sigma_s=20°$ (lower part). The first line shows the *a priori* expectation from the model of Eq. (8), while the second and the third line use the information from the observed angular distribution.

	$n=0$	$n=1$	$n=2$	$n=3$
from SN model	50.5%	38.9%	9.7%	0.9%
g.o.f. from SCVM	8.6%	26.7%	58.5%	81.4%
likelihood ratio $L(n)/L_{max}$	0.35	0.73	0.97	0.98
from SN model	52.3%	37.5%	9.2%	1.0%
g.o.f. from SCVM	8.6%	24.9%	53.8%	87.6%
likelihood ratio $L(n)/L_{max}$	0.14	0.39	0.69	0.92

TABLE III. Relative percentage probabilities to have a given number of ES events in KII data set, estimated from observed angular distribution and theoretical expectation on the fluxes, for 3 hypotheses on $\mathcal{E}_x$.

	$n=0$	$n=1$	$n=2$	$n=3$
$\mathcal{E}_x=\mathcal{E}_{\bar{e}}/2$	52.3%	37.5%	9.2%	1.0%
$\mathcal{E}_x=\mathcal{E}_{\bar{e}}$	40.0%	42.3%	15.3%	2.5%
$\mathcal{E}_x=2\mathcal{E}_{\bar{e}}$	29.0%	43.6%	22.3%	5.1%

D. Speculations

It is interesting to consider at this point some speculative scenarios, to investigate the question under which conditions we can increase the expected number of ES events.

A distinguished astrophysical possibility is that there are main departures from a ''standard'' collapse, and a large part of the emitted energy is not seen by IBD. Let us assume as an extreme case that the electron neutrinos have an average energy of 40 MeV and carry an energy of 1.5×10^{53} erg [44]. The calculation reveals that the increase is not much larger: In KII, we expect $N_{dir}=0.59$ rather than $N_{dir}=0.39$. The reason is simply that oscillations transform the ν_e into ν_μ and ν_τ, and the interaction cross section of these neutrinos is smaller.

Another possibility is to study which adjustment of the ''standard'' scenario goes in the right direction. In particular, one can suggest that the ν_x are more energetic than what we assumed. This does not help for the number of events, but helps a bit to explain the fact that the directional events are among the most energetic ones.

The uncertainties in oscillations provide us with another degree of freedom. It seems to us very difficult to avoid the occurrence of MSW oscillations completely, but if θ_{13} is very small, we could get $P_{ee}=0.3$. The result $P_{ee}=\sin^2\theta_{12}=0.3$ assumes that the mantle of the star at densities of about 10 gr/cc was not essentially modified by the precollapse events. The opposite case seems unlikely, but one could get $P_{ee}=1-\sin^2 2\theta_{12}/2\sim0.6$. However, this does not help to increase N_{dir} with the ''standard'' scenario, and it is of limited use to invoke nonstandard scenarios with energetic ν_e's, since in this case the reaction with oxygen are also called into play, see [45] and [46]. Another case arises if θ_{13} is ''large'' when the neutrino mass spectrum is inverted, rather than ''normal'' as considered previously in the text. In fact, in this hypothesis the IBD events are due to the flux Φ_x, and

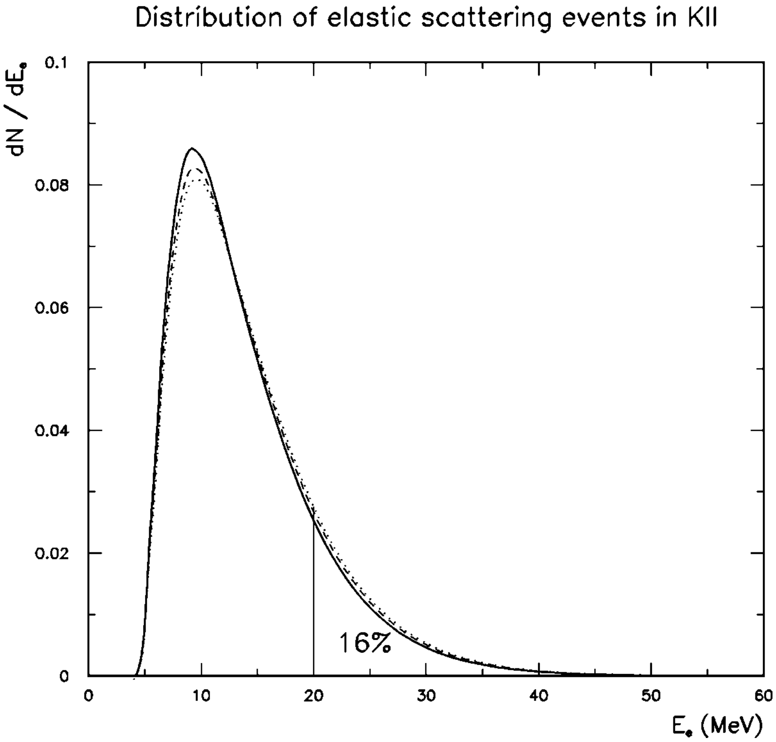

FIG. 6. Expected energy distribution of scattering events in KII, for $\mathcal{E}_x=(0.5,1,2)\times\mathcal{E}_{\bar{e}}$. Also shown is the probability to have one event with energy larger than 20 MeV.

the flux of ν_e (important for ES events) is $0.3\Phi_e+0.7\Phi_x$. Thus, we are interested to consider the possibility of a large $\mathcal{E}_e$ to increase the number of ES events, or the possibility that $\mathcal{E}_e>\mathcal{E}_x$, since in this way we reduce the number of IBD events more than the ES events.

A more drastic attitude is to abandon completely the "standard" idea of the collapse. A specific suggestion made in [38] is that a large amount of neutrino radiation comes from $\pi^+\to\mu^+\nu_\mu$ decay. The largest contribution to scattering events comes from the electron neutrinos, that, due to oscillations originate exactly from ν_μ (in fact, due to the loop-induced difference of potential between τ and μ neutrinos $\nu_\mu\to\nu_1$ and a ν_e happens to be produced with probability $P_{\mu\to e}=0.7$). The ν_μ are monochromatic with energy 29.8 MeV. If the energy injected in ν_μ is 5×10^{53} erg we get about 1 ES event in IMB and 3 ES events in KII (with a few additional oxygen events). Apart from the obvious objection that we need to produce 10^{58} (!) pions, we are left with the problem to explain the main part of the signal (that in the standard interpretation is attributed to IBD).

In summary, we see that there are several interesting possibilities and the fact that we do not have a definitive theory of the collapse motivates their consideration, even though our cursory investigation seems to suggest that it is not so easy to produce radical modifications of the "standard" paradigm.

IV. SUMMARY AND DISCUSSION

We reanalyzed the neutrino signal of SN1987A and in particular the angular distribution in IMB and KII detectors in the light of new facts: namely, improved IBD cross section, neutrino oscillations and a new energy partition between neutrino flavors from the SN (see Sec. I).

Let us summarize the obtained improvement and the residual uncertainties in the description of SN signal. (1) The IBD cross section we use is accurate at about 1%; the traditionally used one just at about 10–20% [18]. As demonstrated in Sec. III A, the new cross section gives a more satisfactory description of the angular distribution of the IMB data, even in absence of an angular bias, or of a contamination due to elastic scattering events. (2) The occurrence of three neutrino oscillations (as defined in Sec. I B) implies that the observed electron neutrinos ν_e are practically purely ν_μ or ν_τ at the production, whereas the observed $\overline{\nu}_e$ flux is composed by 70% of the original $\overline{\nu}_e$ flux, and by 30% of the original $\overline{\nu}_\mu$ or $\overline{\nu}_\tau$ fluxes. The inclusion of neutrino oscillations is crucial in order to account for the elastic scattering events properly, and it is not negligible for IBD events. It should be stressed that the previous papers that analyzed the angular distributions carefully [7,34–38] did not include the effect of the oscillations. The relevance of oscillations will be better assessed after new terrestrial experiments aiming to measure U_{e3} and to determine the neutrino mass hierarchy. (3) But certainly, the astrophysics uncertainties are by far the most important ones. This point is particularly annoying in absence of a theory on SN explosion, and even "reasonable" estimations as those used here should be regarded as provisional at present. In the recent past, an unclear experimental situation has warranted a wide discussion on the impact of neutrino oscillations on supernova neutrinos, rather than on astrophysics. We recall that the new neutrino flux described in Sec. I A has contributed to "solve" certain problems of interpretation related to oscillations, see [48], but has also contributed to refocus the discussion. We believe that in the future, the discussion of SN1987A neutrinos (and presumably, of supernova neutrinos) will gradually shift toward the astrophysical aspects.

The main outcomes of our analysis (Sec. III) can be summarized as follows. The hypothesis that most of the events were due to inverse beta decay is not in disagreement with the observations, although the presence of one or more directional events is suggested by the shape of the angular distributions of IMB and KII experiments.

Even combining the information on the angular distribution with the *a priori* expectation for the number of events within a ''standard'' picture of neutrino emission, an interesting hint that KII dataset includes some elastic scattering events does remain (especially if $\mathcal{E}_x$ is relatively large); see Sec. III C and in particular Tables II and III.

It is conceivable that one can improve the agreement between the angular distribution and the expected (small) number of elastic scattering events by considering non-standard scenarios for the collapse. In the cases we considered in Sec. III D the obtained improvements are interesting, but not dramatic.

Let us finally discuss in detail the indications we obtained on the astrophysical parameters of the collapse, assuming a ''standard'' picture of neutrino emission from here on (Secs. II and III).

We estimated from the data that the average energy of $\overline{\nu}_e$ is about $E_0 = \langle E_{\overline{\nu}_e} \rangle \sim 14$ MeV. This is corroborated in particular by the average energy of IMB events and by the fact that KII sees more events than IMB. Other pieces of data give contrasting hints. In the ''standard'' picture, we interpret these features as due to fluctuations, possibly with the contribution of one or more directional events in the data sets. A reasonable range is $E_0 = 12$–15 MeV, which agrees but is in the low side of the theoretical expectations, Eq. (3). As for the theoretical impact of this result, we note that a low average energy suggests an effective thermalization of the emitted antineutrinos.

The energy emitted in the collapse is about $\mathcal{E}_B \sim (2$–$5) \times 10^{53}$ erg, for a distance of 52 kpc. Interestingly, this value is not far from simple minded theoretical expectations, Eq. (4). Assuming further long wavelength oscillations in mirror neutrinos as in [47] half of the neutrinos become invisible and $\mathcal{E}_B$ should be doubled. Unfortunately, the calculations of $\mathcal{E}_B$ do not seem to be precise enough to disfavor significantly this prediction.

From the hint for elastic scattering event(s) we have some preference toward a comparably larger value of $\mathcal{E}_x > \mathcal{E}_{\overline{e}}$. This is compatible with current expectations, but it is unclear whether a large amount of $\nu_{\mu\tau}$ radiation (that does not produce ''neutrino heating'' for the delayed scenario) can be easily reconciled with the occurrence of the explosion, especially if this happens during the accretion phase.

Finally, it should be noted that there are hints (see [49] and [50]) from astronomy that the distance of the Large Magellanic Cloud traditionally used is overestimated. If the new value of $D = 40$ kpc is adopted, the energy emitted in neutrinos that we estimated has to be reduced by a factor of $(40/52)^2$, namely $\mathcal{E} \sim 1.5 \times 10^{53}$ erg. Having little energy at our disposal is unlikely to help the occurrence of the supernova. This leads us to believe that the old determination of the distance is the correct one (as a matter of fact, more recent works [51,52] argue from astronomical considerations that this is the case).

In conclusion, the ''standard'' picture of neutrino emission and oscillations is not contradicted by SN1987A, and even more, the observed properties of the collapse seem to meet expectations. We believe that there is wide space for deviations from this picture, not only in consideration of the limited statistics but also due to certain features of the observed signals. From the discussion (and also in view of other considerations [53]), it is evident that there is a great interest in obtaining larger samples of elastic scattering events and also of events due to ν_e from the next galactic supernova.

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[44] Indeed, in certain astrophysical scenarios, as collapses with rotation [12], there is a large excess of ν_e at production. What happens is similar to a (very) prolonged neutronization phase; the opacity of the medium is reduced, and energetic electron neutrinos free stream from the star, see also the reviews of V.S. Imshennik published in Astron. Lett. **18**, 489 (1992); Space Sci. Rev. **74**, 325 (1995); and C.L. Fryer and A. Heger, Astrophys. J. **541**, 1033 (2000), in particular their Fig. 12. If we take seriously the fact that the most forward events of KII are also among the most energetic, we are lead to hypothesize that the neutrinos have an average energy about twice as large (which gives $\langle E_e \rangle$) and we obtain $\mathcal{E}_e$ by imposing a reasonable condition on the emitted leptonic number.
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