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Letter to the Editor

The diffuse supernova neutrino background: Expectations and theoretical uncertainties from SN1987A

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ABSTRACT

Context. It has been argued that the detection of the diffuse supernova neutrino background could be imminent. But the theoretical prediction is affected by substantial uncertainties.
Aims. We calculate the signal and its uncertainty with the present configuration of Super-Kamiokande and considering also the possibility of lowering the threshold by Gadolinium loading.
Methods. We model neutrino emission following the analysis of SN1987A of Pagliaroli *et al.* (2009) and use the number of expected events in the neutrino detector as a free parameter of the fit. The best-fit value for this parameter and its error are evaluated by standard maximum likelihood procedures, taking into account properly the correlations.
Results. The uncertainties on the astrophysics of the emission dominates the total uncertainty on the expected signal rate, that conservatively ranges from 0.3 to 0.9 events per year and from 1.1 to 2.9 with Gadolinium.

1. Introduction

Massive stars end their life exploding as core collapse supernovae (SN) and leaving compact remnants, as neutron stars or black holes. The main part of the binding energy is released through neutrino emission, though the details of the emission are not completely understood at present. The SN1987A event gave us the proof that a such signal exists and is detectable [Hirata et al. (1987), Bionta et al. (1987) Alekseev et al. (1988)]. The neutrino signal offers us the best chance to probe this unique astrophysical system.

The neutrino emissions from all the past core collapse supernovae exploded in the Universe cumulate and give rise to the Diffuse Supernova Neutrino Background (DSNB) for which we have promising prospects of detection; for recent reviews and references to the original papers, see Ando & Sato (2004) and Beacom (2010). In order to predict the DSNB signal, two different quantities are needed: the explosion rate of core collapse SNe as a function of the red-shift and the average neutrino emission of the individual supernovas. Each one of these quantities implies an uncertainty on the prediction. Until these are determined, it is not possible to evaluate the reliability of the expectations.

The rate of core collapse supernovae can be identified with rate of formation of massive stars as a function of the red-shift. This quantity, in turn, can be obtained knowing the cosmic history of star formation and the initial distribution of mass. A recent work of Horiuchi *et al.* (2009) used a comprehensive compilation of data to evaluate the uncertainty in this quantity.

The aim of this work is to complement the study of the uncertainties by evaluating the impact of the neutrino emission for an individual supernova. Following Fukugita & Kawasaki (2003), we base our inferences on SN1987A observations using for the analysis the neutrino emission model of Pagliaroli *et al.* (2009). We evaluate the expected signal and its uncertainty for the Super-Kamiokande detector. We consider its present configuration, 22.5 kton of fiducial volume with threshold of $E_{th} = 19.3$ MeV, Malek et al. (2003) and consider the possibility to lower the threshold down to 11.3 MeV thanks to Gadolinium loading as advocated by Beacom & Vagins (2004).

2. The emission in an individual supernova

In this section we determine the $\bar{\nu}_e$ spectrum from SN1987A data, that we will use for the analysis of DSNB. This is done by preliminarily parameterizing the time and energy distribution, then by fitting the data from Kamiokande-II, IMB and Baksan and finally by integrating over the time distribution. The main motivation to this procedure is that we still miss a definitive theory of supernova explosion; thus, despite the paucity of the data from SN1987A, they maintain a very important role to guide our understanding of supernova neutrino manifestations.

The model for supernova emission

Motivated by the prospect of exploring, through the neutrino signal, the physics and astrophysics of the gravitational collapse, we proposed in Pagliaroli *et al.* (2009) a parameterization of $\bar{\nu}_e$ emission, based on the present understanding of emission processes improving the model by Loredo & Lamb (2001). Our model has two emission phases and the $\bar{\nu}_e$ flux is:

$$\Phi_{\bar{\nu}_e}(t, E') = \Phi_a(t, E') + [1 - j_k(t)]\, \Phi_c(t - \tau_a, E'), \tag{1}$$

Here, t is the emission time and E' is the emitted neutrino energy. The first term Φ_a is the flux generated during the phase of accretion and above the shock by the interactions between the positrons and the target neutrons. It describes a radiation from a volume with 3 parameters: the initial accreting mass M_a, the time scale τ_a, the initial temperature of the positrons T_a. The second term Φ_c is the flux coming from the thermal emission of the new born proto-neutron star (i.e., the cooling phase). It describes

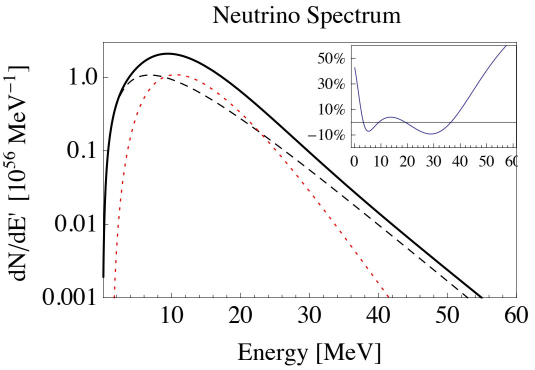

Fig. 1. The SN1987A best-fit spectrum (continuous line) and the two contributions from accretion phase (dotted line) and cooling phase (dashed line). In the inset we plot the percentage difference with the Fermi-Dirac approximation of the spectrum, given in the text.

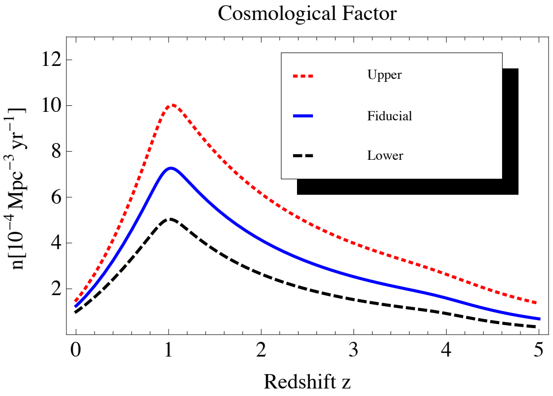

Fig. 2. The cosmological factor n of Eq. (3) for various fits of the Core-Collapse Rate. The continue line is for the Fiducial rate, the dotted line is for the Upper one and the dashed line is for the Lower rate.

a radiation from a surface, proportional to the radius of the neutrino sphere R_c, with a time scale τ_c and the initial temperature of the emitted antineutrinos T_c. Finally the function $j_k(t)$ links smoothly the two emission phases, delaying the cooling emission by τ_a. Analytic expressions of these three functions, Φ_a, Φ_c and $j_k(t)$ are given in Eq. 10, Eq. 13 and Eq. 18 of Pagliaroli *et al.* (2009), respectively. We include neutrino oscillations with normal hierarchy as discussed in Sec. C of Pagliaroli *et al.* (2009).

SN1987A data analysis In Pagliaroli *et al.* (2009), we tested the parameterized model on the small set of events collected in 1987 by Kamiokande-II, IMB and Baksan, leaving aside an interpretation of the events recorded by LSD (Aglietta *et al.* 1987). When we compared the fit based only on the cooling phase, the one adopted in usual SN1987A data analyses, with our fit, we found that the two phases emission model is 50 times more probable (i.e., we got a 2.5σ indication in its favor). Moreover, the best-fit values of the astrophysical parameters, namely $R_c = 16$ km, $M_a = 0.22 M_\odot$, $T_c = 4.6$ MeV, $T_a = 2.4$ MeV, $\tau_c = 4.7$ s, $\tau_a = 0.55$ s, agree well with the general expectations: e.g., the duration of the accretion phase is lower than one second; the radius of the neutrino sphere is similar to the size of the neutron star; the total radiated energy 2.2×10^{53} erg is similar to the binding energy. Finally, the luminosity curve and the mean energy as functions of the time both resemble the results of numerical calculations.

The previous analyses of SN1987A data aimed at predicting DSNB of Lunardini (2006) and Yuksel and Beacom (2007) focused only on the energy spectrum, motivated by the opinion that the time distribution of the events is not relevant. However we will show that our detailed theoretical description of neutrino emission leads to a peculiar integrated spectrum that maintains an imprint of the presence of two different emission phases.

The emission spectrum Putting the best-fit values in the $\bar{\nu}_e$ flux of Eq.(1), integrating in a 30 s time window and on the emitting surface, we obtain the reference spectrum dN/dE' for a single supernova event from SN1987A showed in Fig. 1. We compared this spectrum with a Fermi-Dirac distribution, i.e., $\frac{k}{T^3}\frac{E'^2}{1+\exp(E'/T-\eta)}$. To have the same integral and the same first two momenta of our spectrum, we need $k = 2.97 \times 10^{57}$ a temperature $T = 3.76$ MeV and a pinching factor $\eta = 0.679$. However the percentage difference between the Fermi-Dirac spectrum and our spectrum is not negligible as shown in the inset of Fig. 1. The agreement worsens using the parametrization of Keil *et al.* (2003). The emitted $\bar{\nu}_e$ of our best-fit spectrum have a relatively low energy; indeed, half of them are emitted with neutrino energies below 11.2 MeV. In particular, when we calculate the number of events N_{ev} expected from a galactic supernova assuming an energy threshold of $E_{min} > 6.5$ MeV, $N_{ev} \propto \int dE'\sigma(E)\Phi_{\bar{\nu}_e}$ as a function of the upper extreme of integration E_{max}, we find that there are the 25%, 50% and 75% of the events below E_{max}=14, 18 and 24 MeV, respectively.[1]

3. Expectations for the diffuse neutrino flux

We estimate the diffuse neutrino flux accumulated by all the past supernovae exploded in the Universe assuming that the antineutrino flux discussed in the previous Section represents the typical emission of a core collapse event. In order to do this, firstly we stipulate some standard assumptions on the geometry of the Universe and on the distribution of the considered sources. In a Friedmann-Robertson-Walker flat Universe the expected DSNB flux is:

$$\frac{d\phi(E)}{dE} = \frac{c}{H_0}\int_0 dz \frac{R_{CCSN}(z)}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}\frac{dN(E')}{dE'} \tag{2}$$

The last term of the integrand, dN/dE', is the spectrum of a single SN emission discussed above and calculated for the red-shifted energy $E' = (1+z)E$. The Hubble constant is $H_0 = 71$ km s^{-1}Mpc^{-1}, c is the light speed and the values of the cosmological constants are $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ as measured from the WMAP experiment in Jarosik *et al.* (2010). These assumptions do not introduce significant errors on the predictions.

The key term we have to discuss is $R_{CCSN}(z)$, namely the rate of Core Collapse SN for comoving volume as a function of the red-shift z. This function can be obtained from the number of stars formed in a comoving volume, i.e., from the star formation rate as a function of the red-shift, and from the fraction of stars in the right mass range to give core collapse SNe. Following Horiuchi *et al.* (2009) we adopt the initial mass function of Salpeter (1955) and three different analytic fits for the

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[1] Of course, σ denotes the cross section for the IBD process $\bar{\nu}_e p \rightarrow e^+ n$. We use Eq. 25 of Strumia & Vissani (2003) and throughout the paper, we adopt the approximation $E_{\bar{\nu}_e} = E_{e^+} + 1.3$ MeV, that is adequate for our needs. Unless specified otherwise we always refer to $\bar{\nu}_e$ energy.

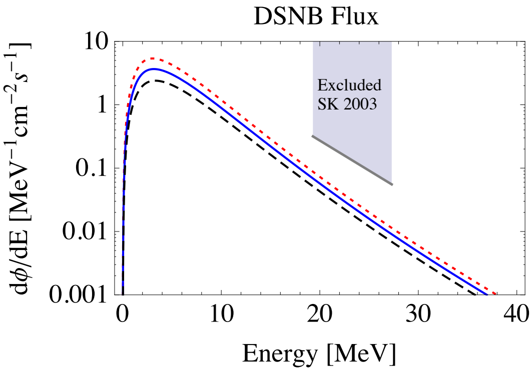

Fig. 3. Expected DSNB flux in logarithmic scale for the three different fits of Core-Collapse Rate. Also shown the upper limit on this quantity given by Super-Kamiokande in 2003 in the energy range between 19.3 and 27.3 MeV Continue, dotted and dashed lines as in Fig. (2).

Rate of Core-Collapse to take into account the astrophysical uncertainty. In Fig.(2) we show the quantity

$$n(z) = \frac{R_{CCSN}(z)}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}, \tag{3}$$

that we call "cosmological factor", namely the first integrand term in Eq. (2). This plot summarizes all relevant assumptions on cosmology and on sources distributions. Horiuchi *et al.* (2009), showed that the use of Kroupa's (2001) or Baldry & Glazebrook (2003) initial mass functions, or the uncertainties in the lowest mass that forms a supernova, introduces only a negligible error in the estimates.

Now we can use Eq. (2) to calculate the flux of Diffuse SN neutrinos background $d\phi/dE$ as a function of the neutrino energy at the Earth. We plot it in Fig. (3) along with the upper bound for the energy region $E > E_{th} = 19.3$ MeV of 1.2 $\bar{\nu}_e$ cm^{-2} s^{-1} obtained by the Super-Kamiokande collaboration (Malek 2003). The total flux of DSNB with the SN1987A best-fit model is $\phi = 27.2$ cm^{-2} s^{-1} for the Fiducial rate. Only $\sim 1\%$ of this flux can be actually observed with a neutrino energy threshold of 19.3 MeV; with the inclusion of Gadolinium the accessible spectrum becomes $\sim 8\%$, showing that most of the flux falls in the very low energy region.

Event rate in Super-Kamiokande We consider the events expected in a detector as Super-Kamiokande, with a fiducial mass of $M_d = 22.5$ kton of water and a detection efficiency ϵ set equal to the 98% above a neutrino energy threshold ($E_{th} = 19.3$ MeV in the present configuration or $E_{th} = 11.3$ MeV by loading the detector by Gadolium). However, note that a scintillator based detector with average chemical formula C_9H_{21} (or $C_6H_3(CH_3)_3$) and with 16 (or 25) kton of mass has the same number of target protons $N_p = 1.5 \times 10^{33}$ and thus the same number of $\bar{\nu}_e p \to e^+ n$ interactions. The event rate is calculated easily

$$\dot{N}_{ev} = N_p \int_{E_{th}} dE \sigma(E) \frac{d\phi}{dE} \epsilon(E). \tag{4}$$

For the best-fit model adopted we expect in Super-Kamiokande the number of events for year reported in Table(1) for two different energy thresholds and for the three different fits for the Rate, namely the best-fit value ranges between 0.39 – 0.65 events for year when we consider a threshold of 19.3 MeV and increases to 1.35 – 2.35 events for year lowering the energy threshold to 11.3 MeV.

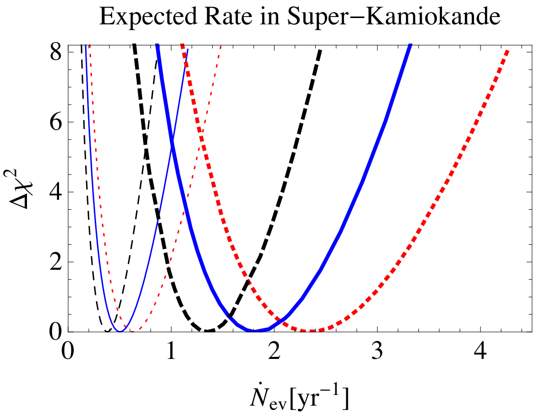

Fig. 4. $\Delta\chi^2$ curves as a function of event rate $\dot{N}_{ev}$ in Super-Kamiokande, as obtained from SN1987A data analysis and for two different energy thresholds. The set of tiny lines is for the present threshold of 19.3 MeV whereas the set with tick lines is for a $E_{th} = 11.3$ MeV. The meaning of the individual lines is as in the previous figures.

4. Uncertainty due to the emission model

In the previous section we discussed the expectations for the DSNB flux based on the SN1987A best-fit model and we considered only the uncertainty related to the Core-Collapse rate.However the data set from SN1987A is small and the procedure of using only the best-fit model is doubtful, until one estimated the associated theoretical error. Indeed, the main aim of this work is to quantify the uncertainty on this prediction due to the emission model. This is an entirely new result and requires to take into account not only the errors associated with the 6 astrophysical parameters of the two emission phases, but also the high correlation between them.

The method used in this work is to insert the rate of expected events in Super-Kamiokande for the DSNB directly in the data analysis of SN1987A. In particular we substitute the parameter R_c, i.e. the radius of the neutrino-sphere, with a function of the others 5 parameters and of the new parameter $\dot{N}_{ev}$, i.e. the rate of expected events in Super-Kamiokande for a fixed energy threshold.

In this way looking for the maximum value of the global likelihood function we obtain the best-fit values for all the 6 parameters and we can calculate the error on the $\dot{N}_{ev}$. To do this we use the marginalization procedure, namely we set a fixed value for $\dot{N}_{ev}$ and we maximize the likelihood function to respect the other 5 parameters. We obtain the behavior of the quantity $\Delta\chi^2 = 2(\ln L_{max} - \ln L)$ where we extract the error range taking into account the degrees of freedom. In Fig.(4) we show the marginalization curves obtained for two different neutrino energy threshold, namely the three tiny lines are for the actual energy threshold of Super-Kamiokande $E_{th} = 19.3$MeV and for the three different fits of the Core-Collapse Rate, whereas the

Table 1. Rate of DSNB events in Super-Kamiokande [yr^{-1}]. Together with the best-fit values we show the 1σ and 2σ statistical errors obtained from marginalization procedure of Sect. 4.

CCSN Rate	$E_{th} = 19.3$MeV	$E_{th} = 11.3$MeV
Upper	$0.65^{+0.23}_{-0.20}(1\sigma)\ ^{+0.51}_{-0.34}(2\sigma)$	$2.35^{+0.59}_{-0.51}(1\sigma)\ ^{+1.24}_{-0.92}(2\sigma)$
Fiducial	$0.51^{+0.18}_{-0.16}(1\sigma)\ ^{+0.40}_{-0.26}(2\sigma)$	$1.82^{+0.46}_{-0.39}(1\sigma)\ ^{+0.97}_{-0.71}(2\sigma)$
Lower	$0.39^{+0.13}_{-0.12}(1\sigma)\ ^{+0.30}_{-0.20}(2\sigma)$	$1.35^{+0.34}_{-0.29}(1\sigma)\ ^{+0.71}_{-0.52}(2\sigma)$

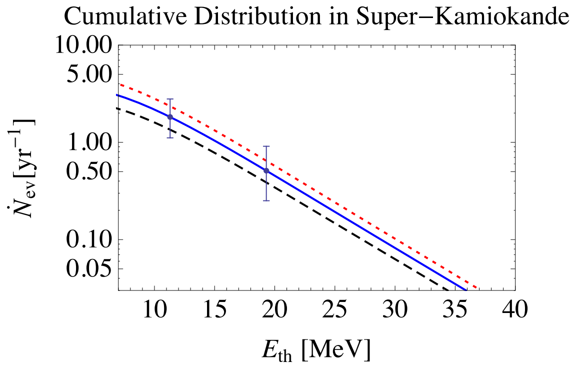

Fig. 5. Cumulative distribution of the events rate in Super-Kamiokande, with the same notation as Fig. (2) for the lines. We give the 2σ error bars on that prediction when E_{th} = 11.3 MeV and = 19.3 MeV.

thick lines are for a threshold of E_{th} = 11.3MeV that can be achieved with gadolinium. The 1σ and 2σ errors found from the $\Delta\chi^2$ curves are reported in Tab.(1).

5. Summary and discussion

In this work we evaluated the signal expected for diffuse supernova neutrino background in Super-Kamiokande and the associated uncertainties, using SN1987A data to constrain the model of neutrino emission. The results are summarized in Fig.(5), where we show the cumulative rate of DSNB events in Super-Kamiokande as a function of the energy threshold for the three different fits of the Core-Collapse Rate.

Following Horiuchi *et al.* (2009) we used the three different fits as a "generous" assessment of the cosmological uncertainty, although we are unable to attach to this range a precise statistical meaning. The result is given in Tab.(1): the cosmological uncertainty is ∼ 25% for the higher threshold and ∼ 27% for the lower threshold, in reasonable agreement with Horiuchi, despite the different emission model used.

On the other hand, selecting the Fiducial cosmological model for the rate, we evaluated the uncertainty on the DSNB due to the emission model. The 1σ (resp. 2σ) percentage error is ∼ 33% (resp. 65%) for the higher threshold and becomes ∼ 23% (resp. 46%) for the lower threshold. The prediction is more precise in the second case since SN1987A data constrain better the low energy region of the spectrum. Curiously, our 2σ ranges are similar to those obtained by Ando & Sato (2004) who use three different emission models obtained from numerical simulations.

It is difficult to combine the two errors in a safe manner, since only the one related to the emission model has a precise statistical meaning. Thus we construct a global range for the expected rate of DSNB events by the following conservative procedure. The upper value of the range is obtained summing the best-fit value for the Upper Core Collapse SN rate and its upward 1σ (resp., 2σ) statistical error; similarly, for the lower value of the range. In particular for E_{th} = 19.3 MeV the expected events rate in Super-Kamiokande ranges between 0.27 (resp., 0.19) events for year and 0.88 (resp., 1.16) events for year, giving a global uncertainty of the ∼ 53% (resp., 95%). For the lower energy threshold E_{th} = 11.3 MeV the range becomes 1.06 – 2.94 (resp., 0.83 – 3.59) events for year with a percentage total error of 47% (resp., 76%). As quantified by the percentage errors, the main amount of this global uncertainty is due to the emission model uncertainty and to the poor statistics of SN1987A data set.

Appendix A: An alternative expression for the rate

We introduce an alternative expression for $\dot{N}_{ev}$ that emphasizes the role of the supernova flux at the source and provides us with some insights. From the emission spectrum dN/dE' we define an effective flux:

$$\frac{d\Phi_*}{dE}(E') \equiv \frac{1}{4\pi d^2 T}\frac{dN}{dE'} \quad \text{with} \quad \begin{cases} d \equiv \sqrt{\frac{c}{4\pi n_* H_0 T}} = 310\ \text{kpc} \\ T \equiv 1\ \text{yr} \end{cases} \tag{A.1}$$

where we introduced the typical value for the cosmic density $n_* = 2 \times 10^{-4}$ SN/(Mpc^3 yr) and the observational time T. By using as an integration variable $E' = E(1 + z)$ (i.e., the neutrino energy at the emission) we rewrite the signal rate in Eq. (4) mimicking closely the signal from a galactic supernova:

$$\dot{N}_{ev} = N_p \int_{E_{th}}^{\infty} dE' \sigma(E') \frac{d\Phi_*}{dE'}(E') \epsilon_*(E') \tag{A.2}$$

where the last function, that plays the role of the efficiency and contains fully the distribution of cosmic supernovae is:

$$\epsilon_*(E') \equiv \int_0^{\frac{E'}{E_{th}}-1} \frac{dz}{1+z}\ \frac{n(z)\ \sigma(E'/(1+z))}{n_*\ \sigma(E')}\ \epsilon(E'/(1+z)) \tag{A.3}$$

This function leads to a severe cut in the rate of events of Eq.(A.2). Just above the energy threshold it can be approximated by a linear function of the energy:

$$\epsilon_*(E') \propto E' - E_{th} \tag{A.4}$$

that corresponds to the fact that DSNB selects the highest energy tail of the spectrum. This remark is important in connection with SN1987A, since we have only a limited information on the highest energy tail of the spectrum (mostly thanks to IMB as remarked also by Fukugita *et al.* 2003) while we know somehow better the spectrum at lower energies. This leads us to expect that by lowering the threshold, not only the number of events will increase but also the accuracy of the predictions based in SN1987A will improve, as illustrated in Fig. 5. Note also that the numerical value of d in Eq. (A.1) agrees with the fact that the DSNB signal is modest.

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