The diffuse supernova neutrino flux

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Abstract. I review the status and perspectives of the research on the diffuse flux of (core collapse) supernova neutrinos (DSNνF). In absence of a positive signal, several upper bounds exist in different detection channels. Of these, the strongest is the limit from SuperKamiokande (SK) of 1.2 electron antineutrinos cm⁻²s⁻¹ at 90% confidence level above 19.3 MeV of neutrino energy. The predictions of the DSNνF depend on the cosmological rate of supernovae and on the neutrino emission in an individual supernova (spectrum, luminosity,...). Above the SK threshold, they range between 0.05 electron antineutrinos cm⁻²s⁻¹ up to touching the SK limit. The SK upper bound constrains part of the parameter space of the supernova rate – and indirectly of the star formation rate – only in models with relatively hard neutrino spectra, while predictions with softer spectra would need bounds stronger by about a factor of ∼4 to be tested. Experimentally, a feasible and very important goal for the future is the improvement of background discrimination and the resulting lowering of the detection threshold. Theory instead will benefit from reducing the uncertainties on the supernova neutrino emission (either with more precise numerical modeling or with data from a galactic supernova) and on the supernova rate. The latter will be provided precisely by next generation supernova surveys up to a normalization factor. Therefore, the detection of the DSNνF is likely to be precious chiefly to constrain such normalization and to study the physics of neutrino emission in supernovae.

1. Introduction
What are our chances to detect neutrinos from core collapse supernovae in the near future? With current and upcoming neutrino telescopes, a high statistics signal is possible if a supernova occurs in our immediate galactic neighborhood. Such event would be as exciting as it is rare: indeed it could require decades of waiting time, since the rate of core collapse in our galaxy is as low as 1-3 supernovae per century (see e.g. [1][2]. A different option is to look for the flux of neutrinos from all supernovae, i.e., integrated over the whole sky. Recently it was shown that the detection of this diffuse supernova neutrino flux (DSNνF) is a concrete possibility [3], which, if realized, could turn the field of supernova neutrinos from the realm of rare events to the territory of a moderately paced and steady progress.

Aside from practical advantages, the study of the DSNνF has an interest of its own, because it would give complementary information, on supernovae and on neutrinos, with respect to an individual supernova burst. Since it contains contributions from several supernovae at different distance and of different morphology, the DSNνF reflects the supernova population of the universe. Thus, from it we could learn about the distribution of core collapse supernovae with the redshift and with the mass of the progenitor. It is known that the supernova rate (SNR) increases with the redshift: supernovae were more numerous in the past than at present, so that as much as ∼ 40% of the DSNνF above the SuperKamiokande detection threshold of
19.3 MeV come from cosmological sources, with redshift \( z > 0.5 \). The distribution in mass goes roughly as the power -2.3 of the progenitor mass, meaning that about 60% of the DSN\( \nu \)F is produced by relatively small stars with mass between lower cutoff of 8 \( M_\odot \) (the minimum mass to have core collapse) and 15\( M_\odot \), with \( M_\odot = 1.99 \cdot 10^{30} \) kg being the mass of the Sun. Thus, data from the diffuse flux would complement those we already have from SN1987A, which had a \( \sim 15 - 20 M_\odot \) progenitor.

By testing the SNR, the DSN\( \nu \)F also probes, indirectly, the history of star formation. Indeed, the SNR is proportional to the star formation rate (SFR), because supernovae progenitors have a very short lifetime, only \( \sim 10^7 \) years (three orders of magnitude shorter than the Sun’s lifetime), negligible with respect to their formation time. Specifically, neutrinos would be precious to learn about the normalization of the SNR, since they are not affected by dust extinction, in contrast with electromagnetic probes. The diffuse flux also offers the theoretical possibility to study the first (Population III) stars \(^4\), since these are believed to have died as core collapse supernovae, and therefore to have contributed to the DSN\( \nu \)F\(^1\).

Similarly to a neutrino burst from an individual galactic source, a detected signal from the DSN\( \nu \)F would provide a large amount of information on the physics of neutrino production, propagation and emission from a supernova. In particular, such signal would add to the SN1987A data in constraining numerical models of supernovae, in testing neutrino oscillations and in probing various effects of physics beyond the standard model such as the existence of new particles and/or new forces. In this paper I will highlight the aspects that are distinctive the diffuse flux, and refer to other contributions in these proceedings for general discussions of the physics potential of supernova neutrinos \(^5\).

2. Experimental status: upper limits

| Experiment, species | Channel | Energy interval | Upper limit (cm\(^{-2}\)s\(^{-1}\)) |
|---------------------|---------|----------------|----------------------------------|
| KamLAND, \( \bar{\nu}_e \) \(^7\) | \( \bar{\nu}_e + p \rightarrow n + e^+ \) | \( 8.3 < E/\text{MeV} < 14.8 \) | \( 3.7 \times 10^2 \) (90% C.L.) |
| SK, \( \bar{\nu}_e \) \(^3\) | \( \bar{\nu}_e + p \rightarrow n + e^+ \) | \( E/\text{MeV}>19.3 \) | 1.2 (90% C.L.) |
| SK/indirect, \( \nu_e \) \(^6\) | \( \nu_e + 16\text{O} \rightarrow 16\text{F} + e^- \) | \( E/\text{MeV}>33 \) | 61-220 (90% C.L.) |
| SK, \( \nu_e \) \(^8\) | \( \nu_e + ^2\text{H} \rightarrow p + p + e^- \) | \( 22.9 < E/\text{MeV} < 36.9 \) | 70 |
| SNO, \( \nu_e \) \(^9\) | \( \nu_e + ^12\text{C} \rightarrow ^12\text{C} + \nu_{\mu, \tau} \) | \( 20 < E/\text{MeV} < 100 \) | \( 3 \cdot 10^7 \) (90% C.L.) |
| LSD, \( \nu_\mu + \nu_\tau \) \(^{10}\) | \( \nu_{\mu, \tau} + 12\text{C} \rightarrow 12\text{C} + \nu_{\mu, \tau} \) | \( 20 < E/\text{MeV} < 100 \) | \( 3.3 \cdot 10^7 \) (90% C.L.) |

So far, the DSN\( \nu \)F has escaped detection. In Table \(^1\) and fig. \(^1\) I summarize the most stringent bounds available on this flux. Thanks to their larger volumes, currently active detectors

\(^1\) The contribution of the first stars would be very hard to detect, since it accumulates in the lowest energy part of the spectrum, where the background dominates.
detectors \[3, 7, 12, 9\] have improved dramatically on the limits set by the previous generation of experiments \[13, 10\]. In particular, the 50 kt of water of SuperKamiokande (SK) has allowed to push the limit on both the $\bar{\nu}_e$ and $\nu_e$ components of the DSN$\nu$F within an order of magnitude or so from theoretical predictions (see Sec. \[3\] for those). The SK data have been analyzed by the SK collaboration in the dominant detection channel, inverse beta decay induced by electron antineutrinos \[3\]. The same data have been used by others to constrain the $\nu_e$ flux by looking for charged-current $\nu_e$ interactions on $^{16}$O \[8\]. Due to the smaller cross section of this process, the resulting limit on the $\nu_e$ flux is looser than the result from inverse beta decay, but it is still interesting as it improves substantially on the older result by LSD \[10\]. With its 1 kt tank of heavy water, SNO could look for $\nu_e$ charged current interactions on deuterium, putting an upper limit comparable with the bound from $\nu_e - ^{16}$O in SK. It has to be noticed, however, that the best constraint on $\nu_e$ from the diffuse flux comes from the constraint on the $\bar{\nu}_e$ component at SK, by considering that the two components must be similar due to their common origin in the non-electron neutrino flavors inside the star through neutrino oscillations \[6\].

The data collected by currently active detectors have not yet been analyzed to constrain the non-electron components of the DSN$\nu$F. On these, the loose limits put by LSD \[10\] (see Table \[1\]), are still the best available. However, considerations of naturalness lead to believe that constraints at the level of those on $\nu_e$ and $\bar{\nu}_e$ should apply to non-electron neutrinos as well.

The main challenge and limiting factor of experimental searches of the diffuse flux is background reduction. At a water Cerenkov detector like SK a search for the diffuse flux
requires to cut all events with energy below 18 MeV (positron energy), due to the high spallation background below that threshold. This excludes the bulk of the flux, which is concentrated at lower energy, $\sim 5$ MeV, causing a huge loss of sensitivity with respect to the ideal case of no background. In the remaining energy window one has to look for the signal induced by the DSN$\nu$F ($\bar{\nu}_e$ component) on top of the ineliminable background from invisible muons and atmospheric neutrinos, which limit the sensitivity further. Similar considerations hold for heavy water. Liquid scintillator allows to single out inverse beta decay events by observing the positron and neutron capture signals in coincidence. This results in a better background reduction and thus explains the sensitivity of KamLAND down to energy of about 8 MeV, which is where the ineliminable background of reactor neutrinos ends 2.

3. Status of theory: flux predictions
The recipe to estimate the DSN$\nu$F is relatively simple: consider the neutrino output of an individual supernova, apply the relevant propagation effects – such as redshift of energy and neutrino oscillations – and then sum over the supernova population of the universe. Formally, this corresponds to the following integral:

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{\text{max}}} R_{\text{SN}}(z) \sum_{w=e,\mu,\tau} \frac{dN_w(E')}{dE'} P_{we}(E,z) \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}},$$

which describes the $\nu_e$ component of the flux differential in the neutrino energy at Earth, $E$. There $dN_w(E')/dE'$ is the flux of neutrinos of flavor $w$ emitted by an individual supernova, differential in the neutrino energy at production, $E'$. $P_{we}$ is the probability that a neutrino produced as $\nu_w$ is detected as $\nu_e$ at Earth, and $R_{\text{SN}}$ describes the SNR per comoving volume. $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$ represent the fractions of energy density of the universe in matter and dark energy respectively, $c$ is the speed of light and $H_0 \approx 70$ Km s$^{-1}$Mpc$^{-1}$ is the Hubble constant.

Many estimates of the DSN$\nu$F according to Eq. (1) have been published in the literature [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. Fig. 2 shows a sample of results for the $\bar{\nu}_e$ component of the flux above the SK threshold, compared with the current SK limit (see Table 1). As it appears in the figure, there is a considerable spread in the flux predictions, which range – considering the errors quoted – roughly between 0.05 cm$^{-2}$s$^{-1}$ and values that even exceed the experimental limit of 1.2 cm$^{-2}$s$^{-1}$, thus resulting in constraints on the input quantities of the calculation (see Sec. 4). This spread reflects the different approaches used by different authors. Specifically, Hartmann and Woosley [21], Ando and Sato [25, 11], Strigari et al. [24] and Olive et al. [28] have used the SNR as it is inferred from measurements of the SFR, while Kaplinghat et al. [22] have estimated the SNR considering the constraints on the universal metal enrichment history. Lunardini [27] used information on the SNR from direct supernova observations only. Different were also the choices of the neutrino spectrum: all the references take the spectra from numerical simulations, with the exception of ref. [27], where only the (softer) spectra that fit the SN1987A data are considered, following the earlier example of Fukugita and Kawasaki [29].

Predictions exist also for the flux of $\bar{\nu}_e$ above energy thresholds lower than the current SK one. These could be relevant for future neutrino telescopes, e.g. SK with Gadolinium addition (see Sec. 5). Table 2 shows the results obtained in ref. [27] for the $\bar{\nu}_e$ flux and the corresponding rate of events from inverse beta decay in SK. From it, one concludes that a lowering of the energy threshold down to $\sim 10$ MeV would represent a large improvement in the flux captured, with no guarantee of a detection, however, due to the smallness of the number of events.

2 This consideration on the reactor neutrino background motivates the initiative of building a large liquid scintillator detector in a de-nuclearized area such as Hawaii, New Zealand or Australia, see e.g. [14].
Flux(E > 19.3 MeV)/(cm$^{-2}$s$^{-1}$)

Figure 2. A sample of theoretical predictions [21, 22, 25, 11, 24, 27, 28] for the $\bar{\nu}_e$ component of the DSN$\nu$F above the SK energy threshold (figure adapted from ref. [27]). The number by Lunardini is quoted with a 99% C.L. error bar. For the other results, the error bars are an indicative description of the uncertainty due to uncertain input parameters; they have no statistical meaning. The SK limit (see Table 1) is shown for comparison.

Table 2. Predictions for the $\bar{\nu}_e$ diffuse flux and for the corresponding rate of inverse beta decay events in SK for different energy thresholds, from ref. [27]. The intervals correspond to 99% C.L. These results were obtained using soft neutrino spectra compatible with the SN1987A data, and therefore lie on the conservative side with respect to predictions that used harder neutrino spectra, motivated by numerical simulations.

| $E > 19.3$ MeV | $E > 11.3$ MeV | $E > 5.3$ MeV |
|----------------|----------------|----------------|
| flux (cm$^{-2}$s$^{-1}$) | 0.05 - 0.35 | 0.33 - 2.1 | 3.2 - 22.6 |
| events/year at SK | 0.09 - 0.7 | 0.27 - 1.6 | 0.43 - 2.2 |

4. What have we learned on supernovae and on neutrinos? What will we learn?

Undoubtedly, the best piece of information that we have, at present, on the DSN$\nu$F is the negative result of SK. Is this upper limit strong enough to give any information? The answer can be read off from fig. 2 there one can see that the SK limit touches some of the theoretical predictions but not others, with the conclusion that only conditional bounds can be put on the SNR (or, indirectly, on the SFR) or on the neutrino emission in a supernova. The situation is illustrated well in fig. 3 taken from ref. [29]. The figure shows how the exclusion region for the SFR varies by varying the neutrino spectrum in the region allowed by SN1987A and the minimum progenitor mass between 8 and 10 $M_\odot$. The space allowed by astrophysical measurements of the SFR, also shown in the figure, is only marginally touched by the most conservative exclusion line, corresponding to the softest neutrino spectrum and 10 $M_\odot$ minimum progenitor mass (“SK Limit Min” in the figure). Some restriction of this space is obtained if the hardest spectrum is used with 8 $M_\odot$ minimum progenitor mass. The conclusions of ref. [27] are analogous. The exclusion found by Strigari et al. [30] is not in constrast with what shown in fig. 3 since these
authors relied on a harder neutrino spectrum, with respect to refs. [29] and [27], motivated by numerical simulations.

Figure 3. Measurements of the SFR compared with the exclusion region obtained from the SK limit on the $\bar{\nu}_e$ diffuse flux (see Table 1), from ref. [29]. The figure shows how the exclusion region changes by varying the input neutrino spectrum in the range allowed by SN1987A. The less stringent exclusion barely touches the astrophysical measurements.

On the side of neutrino physics, the DSN$\nu$F could be the best probe of exotic effects that could manifest themselves only on cosmological distances. An example of this is neutrino decay: it was shown [31, 32] that data from the diffuse flux would be sensitive to a ratio of neutrino lifetime over mass as large as $\tau/m \sim 10^{10}$ s/eV. It was also pointed out [33] that the DSN$\nu$F could reveal the existence of new, light gauge bosons that could be produced in the resonant annihilation of a neutrino and an antineutrino, one of them from a supernova and the other from the cosmological relic neutrino background. A test of dark energy, complementary to astrophysical measurements, is also possible in principle [34]. Many other aspects of the physics of neutrinos and supernovae could be tested with the DSN$\nu$F, similarly to the case of an individual supernova burst. These are illustrated in detail elsewhere in these proceedings [35].

5. Discussion: perspective of future research
What are the likely developments in the study of the DSN$\nu$F in the next 5-10 years?
Progress will be made with new, more sensitive neutrino telescopes. The first to become operational could be the GADZOOKS project [35]: an upgraded configuration of SK employing
a solution of water and Gadolinium trichloride instead of the pure water like the present
detector. The presence of Gadolinium would greatly enhance neutron capture, resulting in better
background discrimination for the search of the $\bar{\nu}_e$ component of the DSN$\nu$F. This would make
it feasible to lower the energy threshold to 11.3 MeV in neutrino energy (10 MeV in positron
energy) and therefore to have a larger event rate, estimated to be as high as 2 $^{[27]}$ or even 6
$^{[35]}$ events/year. The GADZOOKS initiative is progressing with the creation of a dedicated
committee internal to the SK collaboration and the construction of a new test tank made of
stainless steel instead than coated carbon steel as the previously used K2K 1 kt prototype, where
rust made testing impossible $^{[36]}$.

In the space of a decade from now, water Cerenkov detectors of megaton mass, 20 times
larger than SK, could become a reality. Projects of this type are under study: these are
HyperKamiokande $^{[37]}$, UNO $^{[38]}$ and MEMPHYS $^{[39]}$. According to a very conservative
estimate $^{[27]}$, these should have an event rate between 2 and 44 events/year above the current
SK threshold of 19.3 MeV.

A rather intense activity is ongoing to plan large non-water neutrino detectors. One of
these is LENA $^{[40]}$, which, with its 50 kt of liquid scintillator, would have a better background
rejection than SK and a comparable event rate. Detectors using $\sim$ 100 kt of liquid Argon, like
GLACIER $^{[41]}$ and LANNDD $^{[42]}$ would be precious for their sensitivity to the $\nu_e$ component
of the DSN$\nu$F.

On the side of theory, much work has to be done to improve the predictions of the DSN$\nu$F.
To reduce the uncertainty on the estimated diffuse flux, it would be crucial to reduce the
uncertainties on the neutrino fluxes and spectra emitted by an individual supernova. This
could be offered by the advancement of numerical simulations or by data from a future galactic
supernova. Besides knowing better the neutrino emission by a single star, it would be important
to generalize the calculation of the diffuse flux, Eq. (1), to include individual variations of the
neutrino output between different stars, depending on various factors like the progenitor mass,
rotation, magnetic fields, etc.. The uncertainty on the diffuse flux associated with the SNR
will be dramatically reduced when results become available from the next generation supernova
surveys like SNAP $^{[43]}$ and JWST $^{[44]}$. While primarily designed to study type Ia supernovae,
these would see thousands of core collapse supernovae up to redshift $\sim$ 1 and beyond $^{[44]}$.

At the interface between theory and experiment, work is needed to improve the interpretation
of the existing experimental searches: it is necessary to consistently take into account that a
bound on the neutrino flux from an experimental limit on the event rate necessarily depends on
the neutrino spectrum, which is not known precisely at the present time.

Finally, let us review the scenarios that could be realized with new experimental results on
the $\bar{\nu}_e$ component of the DSN$\nu$F and the current theoretical predictions as in fig. 2. Evidence
of the diffuse flux above the SK limit would point in the direction of a neutrino spectrum much
harder than what used in the analysis of the current SK data $^{[3]}$, or would indicate a fluctuation
in the flux due to an extragalactic supernova at moderate distance $^{[2]}$. The latter case could
be distinguished on the basis of the time distribution of the excess flux. A detection of the
neutrino flux anywhere below the SK limit would be very important to discriminate between
the different predictions. To constrain the SNR unambiguously (i.e., to obtain a constraint in
every framework of theory considered so far), would require upper limits on the diffuse $\bar{\nu}_e$ at the
level of $\sim$ 0.3 cm$^{-2}$s$^{-1}$ above the current SK threshold.

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