Supernova neutrino detection in LAr TPCs

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Abstract. The neutrino burst from a core collapse supernova can provide information about the explosion mechanism and the mechanisms of proto neutron star cooling but also about the intrinsic properties of the neutrino such as flavor oscillations. One important question is to understand to which extent can the supernova and the neutrino physics be decoupled in the observation of a single supernova. The possibility to probe the neutrino mixing angle $\theta_{13}$ and the type of mass hierarchy from the detection of supernova neutrinos with liquid argon detectors is summarized in this paper. Moreover, a quantitative study about the possibility to constrain the supernova parameters is presented. A very massive liquid argon detector ($\approx 100$ kton) is needed to perform accurate measurements of these parameters. In addition, these detectors could also provide information on the $\nu_e$ component of the diffuse supernova neutrino background.

1. Introduction
Core collapse supernovae are a huge source of all flavor neutrinos. In 1987 astrophysics entered a new era with the detection of the neutrinos from the supernova SN1987A [1], which exploded in the Large Magellanic Cloud at a distance of $\approx 50$ kpc. The burst of light was visible to the naked eye. About three hours before the light breakout of the supernova (SN), an increase of neutrinos was detected by three water Cerenkov detectors (Kamiokande, IMB and Baksan). This observation confirmed important parts of the neutrino supernova theory such as total energy, mean temperature and time duration. However, limited quantitative information on the neutrino spectrum was obtained due to the small statistics recorded.

The flavor composition, energy spectrum and time structure of the neutrino burst from a supernova can give information about the explosion mechanism and the mechanisms of proto neutron star cooling. In addition, the intrinsic properties of the neutrino such as flavor oscillations can also be studied.

Although new data from neutrino detection have contributed to the understanding of the neutrino properties, still the neutrino mixing angle $\theta_{13}$, the CP violation phase and the nature of the mass hierarchy, i.e., normal (n.h.) or inverted (i.h.), remain unknown. On the other hand, detailed supernova simulations (see e.g. [2]) indicate that the average neutrino energy is flavor dependent and hierarchical ($E_{\nu_e} < E_{\bar{\nu}_e} < E_{\nu_\mu,\tau}, \bar{E}_{\nu_\mu,\tau}$). However, great uncertainties still exist in the spectral and temporal evolution of the neutrino fluxes [3, 4]. The effects of these uncertainties can change dramatically the characteristics of the events observed in a given experiment. Indeed, this dependence can be used to determine the supernova and mixing parameters.

Several studies in the literature concern water, heavy-water or liquid scintillator targets (see e.g. [5]). This paper summarizes the capabilities of liquid argon Time Projection Chamber (LAr TPC) detectors to investigate supernova neutrinos thanks to the simultaneous observation of...
neutrino elastic scattering on electrons and both nuclear charged current and neutral current interactions on argon. While almost all the current detectors are primarily sensitive to \( \bar{\nu}_e \) events, LAr TPCs will provide invaluable information from the \( \nu_e \) detection. The complete study on supernova neutrino detection in LAr TPCs can be found in references [6].

Fundamental physics subjects as neutrino mass hierarchy, CP violation, matter stability, astroparticle physics and in particular, supernova neutrino detection, call for a new generation of very large mass detectors able to collect high statistics and perform detailed event analysis. Among them, LAr detectors of the order of 100 kton will be ideal devices for these purposes offering the widest physics output (accelerator & non-accelerator) [7].

2. Neutrino emission from supernovae

During the gravitational collapse of a supernova, electron neutrinos first and then the rest of flavor neutrinos are produced. It is believed that the 99% of the total binding energy of the star, \( E_B \approx 3 \times 10^{53} \) ergs, is emitted in the form of neutrinos.

Figure 1 shows the prediction for the time evolution of the neutrino fluxes for the different flavors in absence of neutrino oscillations from [8]. The time origin is defined such that the supernova core bounce time corresponds to \( t = 200 \) ms. The early \( \nu_e \) pulse expected in the first 40 ms of the collapse is called shock breakout or neutronization burst and the rest beyond the first 40 ms is considered as the (cooling stage) and it lasts up to \( \sim 10 \) s.

![Figure 1](image.png)

**Figure 1.** Prediction of [8] of the neutrino flux at Earth in absence of neutrino flavor oscillations from a supernova at a distance of 10 kpc.

The neutrinos in the cooling stage are in equilibrium with their surrounding matter density and their energy spectra can be described by a function close to a Fermi-Dirac distribution. The flux of an emitted neutrino \( \nu_\alpha \) can then be written as [4]:

\[
\phi_\alpha(E_\alpha, L_\alpha, D, T_\alpha, \eta_\alpha) = \frac{L_\alpha}{4\pi D^2 F_3(\eta_\alpha) T_\alpha^4} e^{E_\alpha/T_\alpha-\eta_\alpha} + 1
\]  

(1)

where \( L_\alpha \) is the luminosity of the flavor \( \nu_\alpha \) (\( E_B = \sum L_\alpha \)), \( D \) is the distance to the supernova, \( E_\alpha \) is the energy of the \( \nu_\alpha \) neutrino, \( T_\alpha \) is the neutrino temperature inside the neutrinosphere and \( \eta_\alpha \) is the “pinching” factor. We have considered \( \eta_\alpha = 0 \), \( \langle E_{\nu_\alpha} \rangle \approx 3.15 T_\alpha \) and normalization factor \( F_3(0) \approx 5.68 \).
The original $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ fluxes are approximately equal and therefore we treat them as $\nu_x$. An energy hierarchy between the different neutrino flavors is generally believed to hold and imply $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$. However, the specific neutrino spectra remain a matter of detailed calculations. In particular, recent simulations seem to indicate that the energy differences between flavors could be very small and possible collective neutrino flavor conversions could arise for either mass hierarchy depending on the primary fluxes [9].

Neutrino oscillations and matter effects in the supernova will change significantly the neutrino fluxes and therefore, the number of events expected in the detectors. If the neutrino energy spectra are different, then $\theta_{13}$ and the mass hierarchy can be probed. For small mixing angle ($S$) ($\sin^2 \theta_{13} < 2 \times 10^{-6}$), there are no effects on $\theta_{13}$ and we can not distinguish among mass hierarchies. Only an upper bound on $\sin^2 \theta_{13}$ can be set. For intermediate $\theta_{13}$ ($2 \times 10^{-6} < \sin^2 \theta_{13} < 3 \times 10^{-4}$) maximal sensitivity to the angle is achieved and measurements of the angle are possible in this region. For large mixing angle ($L$) ($\sin^2 \theta_{13} > 3 \times 10^{-4}$) maximal conversions occur. The mass hierarchy can be probed but only a lower bound on $\theta_{13}$ can be established.

3. Supernova neutrino detection in terrestrial detectors

Most of the current and near-future supernova neutrino experiments [10] are water Cerenkov or liquid scintillator detectors and therefore, primarily sensitive to the $\bar{\nu}_e$ component of the signal, via inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$. For supernova burst detection, not only statistics but also diversity of flavor sensitivity is needed: neutral current sensitivity, which gives access to the $\nu_\mu$ and $\nu_\tau$ components of the flux, and $\nu_e$ sensitivity are particularly valuable.

Only two near-future experiments will be mainly sensitive to $\nu_e$'s. The HALO detector [11] is under construction at SNOlab and it uses 80 tons of lead blocks instrumented with the unused SNO NCD counters to record neutrons and electromagnetic signals. However, this technique has some limitations since no energy or pointing information can be obtained and only rates are provided. The ICARUS detector at Gran Sasso [12] is a 600 ton LAr TPC with excellent $\nu_e$ sensitivity via $^{40}$Ar CC interactions, for which de-excitation gammas will be visible.

All current supernova neutrino experiments participate to the Supernova Early Warning System (SNEWS) [13], the network of SN neutrino observatories whose main goal is to provide the astronomical community with a prompt alert for the next galactic core collapse supernova explosion.

Very promising for the future are a number of planned mega-detectors exploring essentially three technologies: megaton scale water Cerenkov detectors, like LBNE in DUSEL [14], Hyper-K in Japan [15] and Memphys in Europe [16], 100 kton scale LAr TPC detectors like GLACIER in Europe [17] or LAr LBNE in DUSEL [18] and 50 kton scale liquid scintillator detectors like LENA in Europe [19] or Hanohano in Hawaii [20]. Some such detectors can hope to collect individual neutrino events every few years from beyond the Local Group of galaxies (few Mpc), assuming that background can be reduced sufficiently.

The LAGUNA [21] project in Europe is studying the performances of these three technologies for detecting supernova neutrinos. The three proposed large volume detector neutrino observatories can guarantee continuous exposure for several decades so that a high statistics supernova neutrino signal could be eventually observed. The expected number of events for GLACIER, LENA and MEMPHYS are reported in [22], including the neutronization burst rates and diffuse supernova neutrino background. LAr TPCs provide fundamental information from the $\nu_e$ detection with a very low energy threshold.

4. Supernova neutrino detection in Liquid Argon TPCs

In a liquid argon TPC supernova neutrinos ($E_\nu < 100$ MeV) can be detected through four different channels [6];
(i) Charged current (CC) interactions on argon

\[ \nu_e^{40} {\text{Ar}} \rightarrow e^- + ^{40} K^* \]  \hspace{1cm} (2)

\[ \bar{\nu}_e^{40} {\text{Ar}} \rightarrow e^+ + ^{40} Cl^* \]  \hspace{1cm} (3)

The neutrino energy thresholds of these reactions are 1.5 and 7.48 MeV, respectively.

(ii) Neutral current (NC) interactions on argon

\[ (\nu) ^{40} {\text{Ar}} \rightarrow (\nu) + ^{40} Ar^* \]  \hspace{1cm} (4)

The energy threshold of this reaction is 1.46 MeV.

(iii) Elastic scattering (ELAS) on electrons

\[ (\nu) e^- \rightarrow (\nu) e^- \]  \hspace{1cm} (5)

Figure 2 shows the cross sections of all the processes as a function of the neutrino energy. It is possible to separate the different channels by measuring the associated photons from the $K$, $Cl$ or $Ar$ de-excitation, or by the absence of them in the case of elastic scattering.

Figure 2. Neutrino cross sections relevant to the supernova detection with a liquid argon TPC.

4.1. Neutronization burst in LAr TPCs

The prompt $\nu_e$ burst is in principle observable and represents a diagnostic of the fundamental collapse supernova behavior. LAr TPCs provide unique information about the early breakout pulse due to their excellent sensitivity to $\nu_e$ neutrinos mainly through the CC process. The analysis of the time structure of the supernova signal during the first few tens of milliseconds after the core bounce can provide a clean indication if the full $\nu_e$ burst is present or absent and therefore allows distinguishing between different mixing scenarios.

Figure 3 shows the effect of the reduction of the $\nu_e$ peak due to oscillations. The suppression is maximal in the case of for normal hierarchy and large $\theta_{13}$ mixing angle (n.h.-L) due to the total conversion of $\nu_e$ into $\nu_{\mu,\tau}$. The energy spectrum moves slightly to higher neutrino energy values. Large LAr TPC detectors of the order of 100 kton will be needed to provide enough statistics to study the $\nu_e$ neutrino burst.
Figure 3. Time evolution of the $\nu_e$ CC event rate (left) and the corresponding time integrated event spectra (right) for different oscillation scenarios.

4.2. Cooling phase

The main neutrino emission from core collapse supernovae occurs during the cooling stage. Table 1 shows the expected number of neutrino events from a supernova at 10 kpc in a 100 kton detector. The four detection channels are considered independently and oscillation and non-oscillation cases are computed for normal and inverted hierarchies.

Table 1. Expected neutrino events in a 100 kton detector from a supernova at a distance of 10 kpc.

| Reaction   | No oscillation | Oscillation (n.h.) | Oscillation (i.h.) |
|------------|----------------|--------------------|--------------------|
|            |                | Large $\theta_{13}$ | Small $\theta_{13}$ | Large $\theta_{13}$ | Small $\theta_{13}$ |
| ELAS       | 1330           | 1330               | 1330               | 1330               | 1330               |
| $\nu_e$CC  | 6240           | 31320              | 23820              | 23820              | 23820              |
| $\bar{\nu}_e$CC | 540   | 1110               | 1110               | 2420               | 1110               |
| NC         | 30440          | 30440              | 30440              | 30440              | 30440              |
| Total      | 38550          | 64200              | 56700              | 58010              | 56700              |

A total of 38550 neutrino events are expected in case of no oscillation assuming $\langle E_{\nu_e} \rangle = 11$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle = 25$ MeV and luminosity equipartition. CC events are very sensitive to the change in the energy spectra due to oscillations. A clear increase in the number of events is expected, being a factor 4-5 for $\nu_e$CC events and a factor 2-4 for $\bar{\nu}_e$CC interactions. The main variations with the $\theta_{13}$ angle are expected for the $\nu_e$CC channel in the case of normal hierarchy and for the $\bar{\nu}_e$CC channel for inverted hierarchy. NC
events are not affected by oscillations and they constitute an excellent probe for the supernova properties.

Figure 4 shows the oscillation effects in the neutrino energy spectra of the expected $\nu_e$ CC and $\bar{\nu}_e$ CC events in a 3 kton detector. Due to the total conversion $\nu_{\mu,\tau} \rightarrow \nu_e$ for the n.h.-L case, the $\nu_e$ energy spectra is harder and this leads to a huge increase of the expected events due to the quadratic dependence of the CC cross section with energy. The same effect can be seen for $\bar{\nu}_e$ events and i.h.-L case.

![Figure 4. Expected number of $\nu_e$CC (left) and $\bar{\nu}_e$CC (right) events in a 3 kton LAr detector from a supernova at 10 kpc.](image)

Other models for supernova neutrino fluxes considering MSW flavor conversions have been studied in [6]. Collective oscillations giving rise to spectral swaps and possible Earth matter effects are also considered in recent papers [9]. These effects can produce distortions in the observable supernova neutrino signal and are crucially dependent on the neutrino mass hierarchy and the relative sizes of the primary neutrino spectra.

5. Decoupling supernova and neutrino oscillation physics with LAr TPC detectors

The understanding of the supernova explosion is still plagued by uncertainties which have an impact on the precision with which one can predict time, energy and flavor dependent neutrino fluxes. On the other hand, the neutrino mixing properties are not fully known and in fact large uncertainty exists on the prediction of the actual effect of neutrino oscillations in the event of a supernova explosion. The main question is to understand to which extent the supernova and the neutrino physics can be decoupled in the observation of a single supernova.

In the case of LAr TPCs, the combination of the four independent detection channels can over-constrain the features of the supernova fluxes and the mixing parameters. The capability of LAr TPC detectors to simultaneously measure the supernova and the oscillation parameters is quantitatively analyzed in next sections. A global fit to the event energy distribution for elastic and charged current events and to the rate for the neutral current events is performed.

5.1. Study of the neutrino oscillation parameters

First we investigate the sensitivity to the mixing angle $\theta_{13}$ and the type of mass hierarchy without any assumption on the supernova parameters. We exploit the information from the four neutrino detection channels on argon and we minimize a $\chi^2$ function letting free the five supernova parameters.

In order to understand the uncertainties on the knowledge of the supernova physics, we consider two different sets of reference values for the supernova parameters, corresponding to one hierarchical energy scenario (I) and a non-hierarchical scenario (II). They differ in the
assumptions on the average energies of the neutrino flavors. The luminosities of the neutrino flavors are assumed to be equal.

We first analyze the true small and large mixing angle scenarios and study the possibility of distinguishing the mass hierarchy and putting a bound on the $\theta_{13}$ value.

Figure 5 shows the variation of the minimized $\chi^2$ value with the $\sin^2 \theta_{13}$ parameter and the mass hierarchy for a 100 kton detector. In the top right corner is indicated in bold the “true” scenario considered. The left part of a given plot corresponds to the results of the fit under the assumption of normal hierarchy and the right part for an inverted hierarchy. Solid lines are computed considering the four supernova neutrino detection channels. Dashed lines do not take into account the NC processes. The shaded region illustrates the excluded region by the results of reactor experiments. The one- and two-sigma levels are shown by horizontal lines.

![Figure 5](image_url)

**Figure 5.** $\chi^2$ value of the fit as a function of $\sin^2 \theta_{13}$ for a 100 kton detector. Curves on the left (right) part of every plot correspond to the results of the fit under the assumption of a normal (inverted) hierarchy. Four limiting oscillation scenarios (n.h.-L, n.h.-S, i.h.-L, i.h.-S) are considered as “true” and the reference values of the supernova parameters correspond to scenario I. Solid curves are computed using the information of the four supernova neutrino detection processes and the dashed line does not take into account NC events.

We see that normal and inverted hierarchies are indistinguishable for small “true” $\theta_{13}$ mixing angle. The results of the fit are similar and only an upper bound on $\sin^2 \theta_{13}$ can be set. If the “true” mixing angle is large, we are able to distinguish among hierarchies. Assuming the “true” hierarchy is normal and the value of $\theta_{13}$ is large (n.h.-L), we could put a lower limit on the $\theta_{13}$ angle. The same is possible for the case of inverted hierarchy. The wrong hierarchies are excluded. We illustrate the importance of the NC events. If we do not include them, we lose sensitivity in the large mixing angle cases and i.h.-L could be misidentified as n.h.-S.

The sensitivity to the oscillation parameters is almost similar for hierarchical (scenario I) and non-hierarchical scenarios (scenario II): $\langle E_{\nu_e}\rangle = 13$ MeV, $\langle E_{\nu_x}\rangle = 16$ MeV, $\langle E_{\bar{\nu}_e}\rangle = \langle E_{\bar{\nu}_x}\rangle = 17.6$ MeV considering a 100 kton detector. Table 2 shows the results on the determination of the $\theta_{13}$ mixing angle for the different oscillation cases.

If the $\theta_{13}$ mixing angle is in the intermediate range ($2 \times 10^{-6} < \sin^2 \theta_{13} < 3 \times 10^{-4}$), maximal
scenario I (assuming true $\sin^2\theta_{13}$ and $2\sigma$ levels for scenario I (assuming true $\sin^2\theta_{13} = 10^{-4}$):

\[
\begin{align*}
9.1(8.1) \times 10^{-5} &< \sin^2\theta_{13} < 1.1(1.3) \times 10^{-4} & \text{1}\sigma(2\sigma) & \text{assumed n.h.} \quad (6) \\
8.9(7.4) \times 10^{-5} &< \sin^2\theta_{13} < 1.1(1.3) \times 10^{-4} & \text{1}\sigma(2\sigma) & \text{assumed i.h.} \quad (7)
\end{align*}
\]

Table 2. Estimated limit on the $\theta_{13}$ mixing angle at 1$\sigma$ for different “true” oscillation cases with a 100 kton detector. We compare the results considering as reference values for the supernova neutrino parameters scenarios I (hierarchical) and II (non-hierarchical).

| Determination of $\sin^2\theta_{13}$ and mass hierarchy (SN parameters free) | True osc. case | SN scen. I | SN scen. II |
|---|---|---|---|
| n.h.-L | $> 4.5 \times 10^{-4}$ n.h. | $> 1.8 \times 10^{-4}$ n.h. | excluded i.h. | excluded i.h. |
| n.h.-S | $< 4.3 \times 10^{-6}$ n.h. | $< 1.2 \times 10^{-5}$ n.h. | $< 5.9 \times 10^{-6}$ i.h. | $< 4.3 \times 10^{-6}$ i.h. |
| i.h.-L | excluded n.h. | excluded n.h. | $> 5.0 \times 10^{-4}$ i.h. | $> 2.3 \times 10^{-4}$ i.h. |
| i.h.-S | $< 4.0 \times 10^{-6}$ i.h. | $< 9.0 \times 10^{-6}$ n.h. | $< 4.0 \times 10^{-6}$ i.h. | $< 4.1 \times 10^{-5}$ i.h. |

sensitivity to the angle is achieved and measurements of the value are possible. Considering a 100 kton detector, statistically accurate measurements can be performed at 1$\sigma$ and 2$\sigma$ levels for scenario I (assuming true $\sin^2\theta_{13} = 10^{-4}$):

The wrong hierarchies are excluded in both cases. For scenario II, a measurement of the angle is also possible at the 1$\sigma$ level and the mass hierarchy is well determined.

5.2. Study of the supernova parameters

First we study the information about the astrophysical parameters that can be extracted from the detection of supernova neutrinos considering that the oscillation parameters $\sin^2\theta_{13}$ and the mass hierarchy have been determined from reactor and long-baseline experiments.

Assuming that the angle has been measured with a precision of 10% ($\sin^2\theta_{13} = 10^{-3} \pm 10^{-4}$) and the mass hierarchy is also known, we perform a $\chi^2$ minimization letting the supernova parameters free in order to see how well we can constrain them. The expected accuracies at 90% C.L. are summarized in table 3. With the statistics given by a 100 kton detector, all the variables can be measured in a certain range, independently on the supernova scenario. Only the $L_e/L_x$ parameter in the case of i.h. is less well determined for scenario II ($\sim 32\%$) than for scenario I ($\sim 9\%$).

Another possibility is that future neutrino experiments will not be sensitive enough to measure $\sin^2\theta_{13}$ and will place an upper limit on its value. Assuming the limit $\sin^2\theta_{13} < 10^{-4}$, figure 6 shows the allowed regions at 68%, 90% and 99% C.L. on different supernova parameters planes for a 100 kton detector in the case of i.h. Thanks to the high statistics available with a very massive detector, we can fit very precisely the data and the results are essentially equal for both mass hierarchies. For non-hierarchical scenarios, the uncertainties are bigger, specially for the ratio between the electron and non-electron neutrino luminosities.

Finally we investigate the information that can be extracted from supernova neutrinos if a supernova explosion occurred nowadays when the value of the oscillation parameters is unknown. Letting all parameters $\{E_B, \langle E_{\nu_e} \rangle, \langle E_{\bar{\nu}_e} \rangle, \langle E_{\nu_x} \rangle, L_e/L_x, \sin^2\theta_{13}, \sign(\Delta m^2_{32})\}$ freely vary, we study how well we can determine them in the case of a 100 kton detector. The results show
Table 3. Expected accuracies at 90% C.L. in the determination of the supernova parameters using the neutrinos measured with a 100 kton detector. We have assumed that the mass hierarchy is known and the $\theta_{13}$ mixing angle has been measured by terrestrial experiments, being equal to $\sin^2 \theta_{13} = 10^{-3} \pm 10^{-4}$. Supernova scenarios I and II are tested.

| True hierarchy | SN scen. | $\Delta \langle E_{\nu_e} \rangle / \langle E_{\nu_e} \rangle$ (%) | $\Delta \langle E_{\bar{\nu}_e} \rangle / \langle E_{\bar{\nu}_e} \rangle$ (%) | $\Delta E_B / E_B$ (%) | $\Delta (L_e/L_x)$ ($L_e/L_x$)(%) |
|---------------|----------|-------------------------------|-----------------------------|-------------------|---------------------------|
| n.h. I        | 14       | 4                             | 1                           | 2                | 11                        |
| i.h. I        | 5        | 9                             | 1                           | 2                | 9                         |
| n.h. II       | 9        | 3                             | 1                           | 4                | 12                        |
| i.h. II       | 6        | 6                             | 1                           | 2                | 32                        |

Figure 6. 68%, 90% and 99% C.L. allowed regions for the supernova parameters with a 100 kton detector, assuming that an upper limit on the value of the $\theta_{13}$ mixing angle has been set ($\sin^2 \theta_{13} < 10^{-4}$) and the mass hierarchy is inverted ($\Delta m_{31}^2 < 0$). Crosses indicate the value of the parameters for the best fits.

that with large statistics it is possible to decouple the supernova and oscillations physics and determine the value of the parameters with high precision (table 4).

The expected accuracies are similar to the ones obtained constraining the mixing angle and the mass hierarchy, except for the $\langle E_{\nu_e} \rangle$ parameter and n.h.-L. In this scenario, the knowledge of the $\theta_{13}$ value improves the determination of the $\langle E_{\nu_e} \rangle$ energy from 17% to 14% for scenario I and from 21% to 9% for scenario II.

6. Diffuse supernova neutrino background in LAr TPCs

The diffuse supernova neutrino background (DSNB) is the flux of neutrinos and antineutrinos emitted by all core-collapse supernovae occurred so far in the Universe. It will appear isotropic and time independent in feasible observations.

The DSNB has not been detected yet. The Super-Kamiokande experiment established an
Table 4. Expected accuracies at 90% C.L. in the determination of the supernova parameters using the neutrinos measured with a 100 kton detector. No conditions on the $\theta_{13}$ angle and mass hierarchy have been considered.

| True osc. case | SN scen. | $\Delta\langle E_{\nu_\alpha}\rangle / \langle E_{\nu_\alpha}\rangle$ (%) | $\Delta\langle E_{\bar{\nu}_e}\rangle / \langle E_{\bar{\nu}_e}\rangle$ (%) | $\Delta\langle E_{\nu_x}\rangle / \langle E_{\nu_x}\rangle$ (%) | $\Delta E_B / E_B$ (%) | $\Delta(L_e/L_x) / (L_e/L_x)$ (%) |
|----------------|----------|---------------------------------|---------------------------------|---------------------------------|-----------------|---------------------------------|
| n.h.-L         | I        | $\sim 17$                       | $\sim 4$                        | $< 1$                           | $\sim 2$        | $\sim 11$                       |
| i.h.-L         | I        | $\sim 5$                        | $\sim 9$                        | $< 1$                           | $\sim 2$        | $\sim 9$                        |
| n.h.-S         | I        | $\sim 6$                        | $\sim 4$                        | $< 1$                           | $\sim 1$        | $\sim 11$                       |
| i.h.-S         | I        | $\sim 5$                        | $\sim 4$                        | $< 1$                           | $\sim 2$        | $\sim 9$                        |
| n.h.-L         | II       | $\sim 21$                       | $\sim 3$                        | $< 1$                           | $\sim 4$        | $\sim 14$                       |
| i.h.-L         | II       | $\sim 6$                        | $\sim 9$                        | $< 1$                           | $\sim 2$        | $\sim 34$                       |
| n.h.-S         | II       | $\sim 11$                       | $\sim 5$                        | $< 1$                           | $\sim 2$        | $\sim 35$                       |
| i.h.-S         | II       | $\sim 8$                        | $\sim 4$                        | $< 1$                           | $\sim 2$        | $\sim 37$                       |

upper limit on the $\bar{\nu}_e$ flux of $\Phi(\bar{\nu}_e) < 1.2 \text{ cm}^{-2}\text{s}^{-1}$ for neutrino energies higher than 19.3 MeV [23], close to the predictions. If Super-Kamiokande is modified with dissolved gadolinium to reduce detector backgrounds and increase the energy range for analysis, then the DSNB could be detected at a rate of a few events per year.

LAr TPCs would be able to mainly detect the $\nu_e$ component of the DSNB signal providing complementary information with respect to Super-Kamiokande. The main background sources for these events in the relevant neutrino energy range of 10-50 MeV are solar and low energy atmospheric neutrinos. Depending on the theoretical predictions for the DSNB flux, a 100 kton LAr detector running for five years would get more than 4$\sigma$ measurement of the DSNB flux [24].

7. Conclusions
Liquid argon TPC detectors have excellent capabilities to study and decouple supernova and neutrino oscillation physics by the observation of four independent channels: elastic scattering on atomic electrons, charged current interactions on argon (independently sensitive to $\nu_e$ and $\bar{\nu}_e$ neutrinos) and neutral current interactions on argon.

We have studied the sensitivity to the $\theta_{13}$ and mass hierarchy parameters and found that for large mixing angle, the mass hierarchy can be identified and lower limits on the $\theta_{13}$ value are set. For small mixing angle, it is not possible to distinguish the mass hierarchy but upper limits on $\theta_{13}$ can be obtained. If the mixing angle is in an intermediate range, measurements of its value are possible. The statistics provided by the detection of a supernova at 10 kpc with a 100 kton LAr detector allow to quantitatively determine the neutrino oscillation parameters.

Finally we have studied the ability to measure the supernova parameters with good precision using large LAr detectors. Thanks to the high sensitivity to $\nu_e$ neutrinos, these detectors can play a crucial role providing fundamental information about the shock breakout mechanism. With a 100 kton detector, a single supernova explosion would allow determination of the supernova cooling phase quite precisely. In addition, the diffuse supernova neutrino background signal could be observed in five years at the 4$\sigma$ level.

In conclusion, the information from the $\nu_e$ spectrum observed at a LAr TPC will probe features of the supernova neutrino signal that are not accesible to a $\bar{\nu}_e$ detector. The complementary physics potential of large future neutrino detectors will offer unprecedented opportunities to understand the physics of neutrinos and their conversions during a stellar collapse.
References

[1] Hirata K et al. 1987 Phys. Rev. Lett. 58 1490; Bionta R et al. 1987 Phys. Rev. Lett. 58 1494; Alekseev E N et al. 1987 JETP Lett. 45 589
[2] Takahashi K et al. 2003 Astrop. Phys. 20 189-193
[3] Raffelt G G et al. 2003 Preprint astro-ph/0303226; Takahashi K et al. 2003 Phys. Rev. D 68 113009
[4] Lunardini C and Smirnov A Y 2003 J. Cosmol. Astropart. Phys. JCAP06(2003)009
[5] Totani T et al. 1998 Astrophys. J. 496 216; Minakata H et al. 2002 Phys. Lett. B 542 239; Dutta G et al. 2001 Phys. Rev. D 64 073011; Bandyopadhyay A et al. 2003 Preprint hep-ph/0312315
[6] Gil-Botella I and Rubbia A 2004 J. Cosmol. Astropart. Phys. JCAP08(2004)001; Gil-Botella I and Rubbia A 2003 J. Cosmol. Astropart. Phys. JCAP10(2003)009; Bueno A, Gil-Botella I and Rubbia A 2003 Preprint hep-ph/0307222
[7] Rubbia A 2003 Preprint hep-ph/0402110
[8] Thompson T A, Burrows A and Pinto P A 2003 Astrophys. J. 592 434
[9] Choubey S et al. 2010 Preprint arXiv:1008.0308 [hep-ph]
[10] Scholberg K 2010 J. Phys.: Conf. Series 203 012079
[11] Duba C A et al. 2008 J. Phys.: Conf. Series 136 042077
[12] Aprili P et al. 2001 LNGS-EXP 13/89 add. 2/01, CERN-SPSC-2002-027 (SPSC-P-323)
[13] Antonioli P et al. 2004 New. J. Phys. 6 114
[14] Maricic J 2010 J. Phys.: Conf. Series 203 012109
[15] Nakamura K 2003 Int. J. Mod. Phys. A 18 4053
[16] Bellefon A et al. 2006 Preprint hep-ex/0607026
[17] Rubbia A 2009 J. Phys.: Conf. Series 171 012020
[18] Baller B 2010 These proceedings
[19] Marrodan Undagoitia T et al. 2006 J. Phys.: Conf. Series 39 278-280
[20] Maricic J 2010 J. Phys.: Conf. Series 203 012137
[21] Rubbia A 2010 Acta Phys. Polon. B 41 1727-1732
[22] Antiero D et al. 2007 J. Cosmol. Astropart. Phys. JCAP0711(2007)011
[23] Malek M et al. 2003 Phys. Rev. Lett. 90 061101
[24] Cocco A G et al. 2004 J. Cosmol. Astropart. Phys. JCAP12(2004)002