

# Supernova Neutrino Detection With Liquid Scintillators

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**Abstract.** Core collapse supernovae are a remarkable source of neutrinos. These neutrinos can also be detected by means of massive liquid scintillators located underground. Observations of supernova neutrinos can shed light on the explosion mechanism and on neutrino properties. In this paper we review the detection channels for neutrinos in liquid scintillators. We consider present and future experiments for supernova neutrino searches.

## 1. Underground massive liquid scintillator detectors

The technology of massive ( $> 100$  tons) organic liquid scintillators in operation underground has been developed over the last 30 years through a number of detectors: the Baksan observatory [1] in Russia; LVD [2] and Borexino [3] at the Gran Sasso laboratory in Italy; KamLAND [4] at Kamioka, Japan; and, MiniBooNE [5] at Fermilab. This latter in particular is located in a shallow site. The physics search of these detectors can be divided as follows.

- Solar neutrinos to search for neutrino properties and understand the physics of the sun.
- Electron antineutrinos from reactors to search for neutrino properties.
- Detection of neutrinos from a far away accelerator.
- Geo-neutrinos to understand the origin of the heat radiated by the earth and the reservoirs of U and Th within the mantle of the earth.
- Rare processes:
  - Neutrinos from core collapse supernovae.
  - Non-standard neutrino interactions
  - Diffuse neutrino background
  - Muon-induced neutrons and radioactive isotopes
  - Neutrinoless double beta decay.

So in general supernova neutrinos is not the main research goal of these massive projects due to the fact that a galactic supernova is a rare event. These detectors make use of a large volume of organic solvent,  $C_nH_{2n}$ , with  $\rho \sim 0.8$  g/cm<sup>3</sup>. The detector's design can be segmented or unsegmented. LVD is an example of a segmented detector which consists of stainless steel tanks ( $1 \times 1 \times 1.5$  m<sup>3</sup>) each equipped with 3 photomultipliers; the total mass is about 1 kton with  $9.34 \times 10^{31}$  protons and  $4.23 \times 10^{31}$  C nuclei. Borexino is an example of an unsegmented detector with 300 tons of scintillator contained inside a thin nylon spherical vessel; the scintillator is viewed by about 2000 photomultipliers. In this case, in order to reduce the external background,

the scintillator is shielded by a buffer volume and an outer water Cherenkov veto. The detection threshold of each apparatus depends on the main physics goal: in LVD it is 4 MeV; in KamLAND 1 MeV; in Borexino 200 keV.

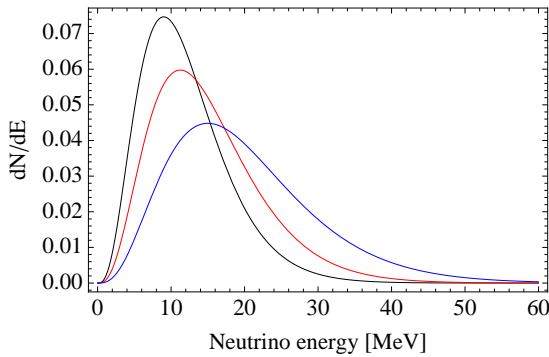
A galactic core collapse supernova is a rare event. Therefore, a supernova observatory must be in operation for more than a decade. The design in this case is important to guarantee a constant high duty cycle. The Baksan observatory has been in operation for 25 years and LVD for 15 years. A number of new projects are under consideration for the future: SNO+ [6] at SNOlab in Canada and LENA [7] proposed for an underground laboratory in Finland. In Tab. 1 we summarize some of the main characteristics of the present and future massive liquid scintillator detectors. In particular, among the future projects SNO+ is expected to be operational after 2012. The next observation of supernova neutrinos hopefully should give the opportunity to measure the binding energy and the temperature (average energy) of the different kind of neutrinos ( $\nu_e$ ,  $\bar{\nu}_e$  and  $\nu_{x=\mu,\tau}$ ).

**Table 1.** Summary of the main characteristics of massive liquid scintillator detectors for supernova neutrino searches.

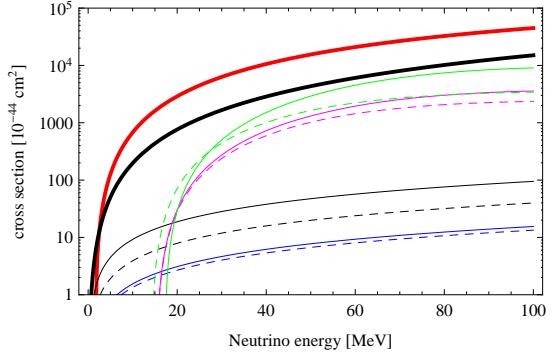
	Type	Target mass [tons]	Threshold [MeV]	Rate above threshold [s <sup>-1</sup> ]	$\Delta E/E$ @10MeV [%]
Baksan Obs.	segmented	330			
		inner core 130	8	0.02	15
LVD	segmented	1000	4	0.03( >10 MeV)	14
		$9.34 \times 10^{31}$ p $4.23 \times 10^{31}$ C			
Borexino	unsegmen.	300	0.25	0.02(>1 MeV)	1.4
		$1.81 \times 10^{31}$ p $1.35 \times 10^{31}$ C			
KamLAND	unsegmen.	1000	1	0.02 >1 MeV	2
MiniBooNE	unsegmen.	800	5	0.03 >5 MeV	2.4
SNO+	unsegmen.	780	0.25	-	-
LENA	unsegmen.	50000	0.25	-	-
		design	design	-	-

## 2. Interaction channels for supernova neutrino detection with liquid scintillators

In this Section we briefly review the detection channels for supernova neutrinos in liquid scintillators. Before discussing the different reactions we report about the reference supernova chosen in this paper. In our case the binding energy is equal to  $E_b = 3 \times 10^{53}$  ergs with  $\langle E_{\nu_e} \rangle = 12$  MeV,  $\langle E_{\bar{\nu}_e} \rangle = 15$  MeV and  $\langle E_{\nu_x} \rangle = 20$  MeV. In Fig. 1 we show the time-integrated energy spectra for the reference supernova. For more details on supernova neutrino spectra we invite the reader to refer to more specific papers in this proceedings.



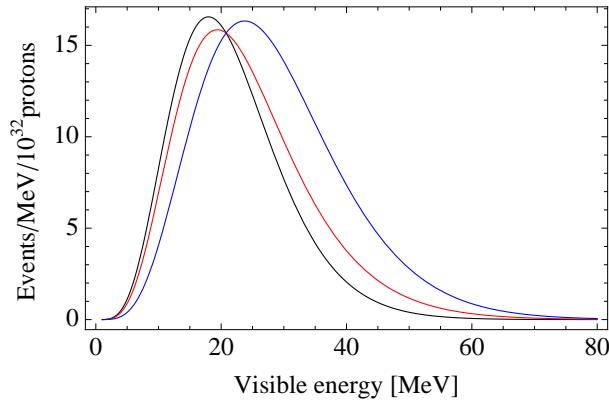
**Figure 1.** Reference supernova neutrino time integrated energy spectra used in the paper. From left to right:  $\nu_e$ ,  $\bar{\nu}_e$  and  $\nu_x$ .



**Figure 2.** Cross sections of the main detection reactions for supernova neutrinos in liquid scintillators. See text for details.

### 2.1. Inverse-beta decay

In this case the reaction is:  $\bar{\nu}_e + p \rightarrow e^+ + n$  with a threshold of 1.806 MeV. The neutron is captured on hydrogen in about 250  $\mu$ s producing a 2.22 MeV gamma-ray. The prompt (positron) and delayed (2.22 MeV gamma-ray) signals increase the tagging power of this reaction. The cross section as a function of energy is shown in Fig. 2 (first red thick solid line from left). About 340 events without oscillations are expected for  $10^{32}$  target protons for a supernova at 10 kpc. A target mass of  $10^{32}$  protons corresponds to about 1 kton detector. In Fig. 3 we show the predicted spectra for three scenarios: no oscillations, normal hierarchy and inverted hierarchy. As it can be seen neutrino oscillations affect the neutrino spectra and fluence. However, the possibility to detect such an effect depends at some extent on the supernova model taken as reference and on the statistics of the detected neutrino sample.



**Figure 3.** Neutrino spectra predicted for the inverse-beta decay detection channel for three scenarios. From left to right: no oscillations, normal hierarchy and inverted hierarchy (small  $\theta_{13}$ )

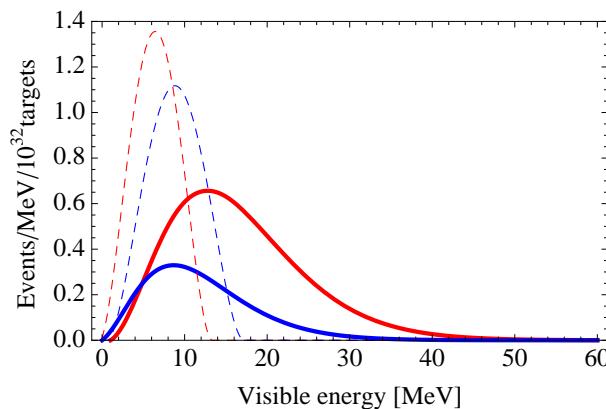
### 2.2. Charged current on $^{12}C$

Liquid scintillators are rich in  $^{12}C$ . The cross section for neutrino interactions on carbon are large ( $\sim 10^{-42}$  cm $^2$ , solid and dashed lines in green below the thick lines in Fig. 2). This offers the possibility to make use of neutrino on carbon interaction channels to search for supernova neutrinos. In particular, we have two charged-current reactions:  $\nu_e + ^{12}C \rightarrow e^- + ^{12}N$  with threshold equal to 17.34 MeV and  $\bar{\nu}_e + ^{12}C \rightarrow e^+ + ^{12}B$  with threshold equal to 14.39 MeV. Both

reactions can be tagged by means of a prompt-delayed sequence due to the  $^{12}\text{N}$  and  $^{12}\text{B}$   $\beta$  decays with 11 ms and 20.2 ms half-life, respectively. The expected number of events for  $10^{32}$  target nuclei and a 10 kpc supernova are less than 30 in each case at most. The prompt-delayed tagging could be used to distinguish  $\nu_e$  against  $\bar{\nu}_e$ . However, as it is shown in Fig. 4, this goal is very difficult to achieve without a very large sample of events. Therefore, considering the mass of present detectors this possibility could be exploited by future super-massive experiments such as LENA.

### 2.3. Neutral current on $^{12}\text{C}$

The neutral current on  $^{12}\text{C}$ ,  $\nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}^*$ , produces an unambiguous supernova neutrino signal by means of a gamma-ray at 15.11 MeV. The cross section is large but smaller than the charged current reactions (magenta solid and dashed lines below the charged current ones in Fig. 2). However, the degeneracy between the average neutrino energy and the supernova luminosity does not allow to measure these parameters independently. We predict about 70 events for  $10^{32}$  target nuclei and a 10 kpc supernova.



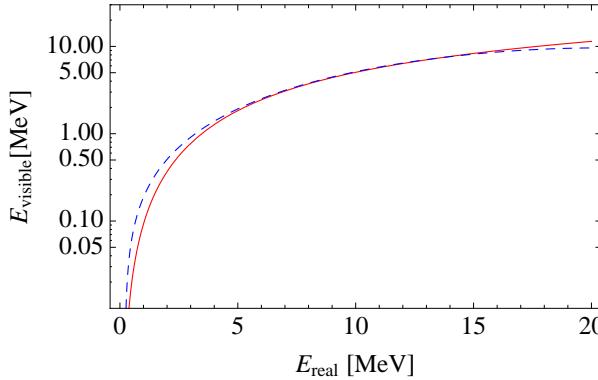
**Figure 4.** Spectrum of prompt (solid lines) and delayed (dashed lines) signal for charged current interactions on  $^{12}\text{C}$ .

### 2.4. Neutrino-electron elastic scattering

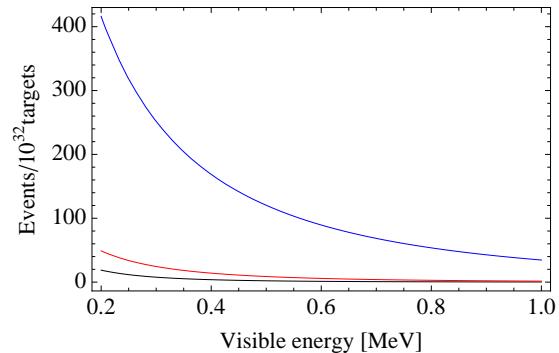
The neutrino-electric scattering have charged current and neutral current channels. These interactions have smaller cross section with respect to all others: lower curves in Fig. 2. There is no specific tagging. Therefore, this interaction channel gives only a minor contribution to the present detectors in supernova neutrino search.

### 2.5. Neutrino-proton elastic scattering

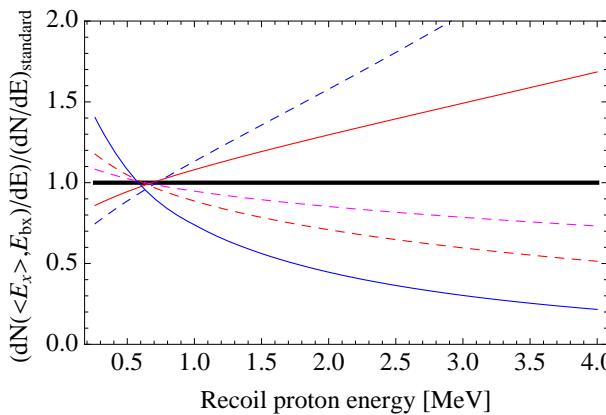
The neutrino-proton elastic scattering for supernova neutrinos in liquid scintillators was first proposed in 2002 [8]. This is a special detection channel for high purity liquid scintillators. The visible energy due to the scintillation produced by recoiled protons shifts the observed spectrum toward lower energies. In Fig. 5 we show the visible energy against the real proton energy measured for KamLAND and Borexino. As it can be seen the effect of quenching is large and this needs a sub-MeV detection threshold. In Fig. 6 we show the expected spectrum using the function in Fig. 5. This figure shows that above 0.3 MeV only  $\nu_x$ 's give a contribution. Because of this effect the degeneracy between the binding energy and the average energy of  $\nu_x$ 's is broken. This is clearly shown in Fig. 7 where we have determined the ratio for a given  $E_x$  and  $T_x$  to the standard case ( $0.5 \times 10^{52}$  ergs and 20 MeV). About 100 events are expected above 0.25 MeV for  $10^{32}$  target protons and a 10 kpc supernova.



**Figure 5.** Visible energy against real energy due to quenching for proton scintillation prompt energy. Solid line: KamLAND. Dashed line: Borexino (preliminary).



**Figure 6.** Spectrum of prompt signal due to neutrino-proton elastic scattering. From right to left:  $\nu_x$ ,  $\bar{\nu}_e$  and  $\nu_e$ .



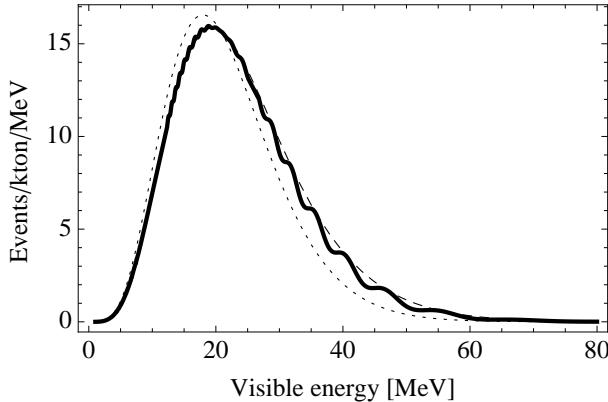
**Figure 7.** Ratio of spectra from neutrino-proton elastic scattering for given binding energy  $E_x$  and temperature  $T_x$  to the standard case described in the paper.

### 3. Regeneration effect through the earth

One feature of neutrino oscillations which is of particular value in this context is the regeneration through the earth. This effect produces a distortion of the spectrum which is a clear signal of neutrino oscillations. In Fig. 8 we show an example of the regeneration process. The possibility to detect supernova neutrinos with more than one experiment from different locations offers the opportunity to compare different spectra and enhance the oscillation process for the case where neutrinos cross the earth. The magnitude of this effect depends on the supernova location with respect to the earth, on the fluence, on the detector performances (such as energy resolution and efficiency) and on the oscillation scenario. At present, considering the target masses of the detector in operation and the uncertainty on the supernova parameters (binding energy and neutrino temperatures), it is not clear how well this regeneration process can be observed.

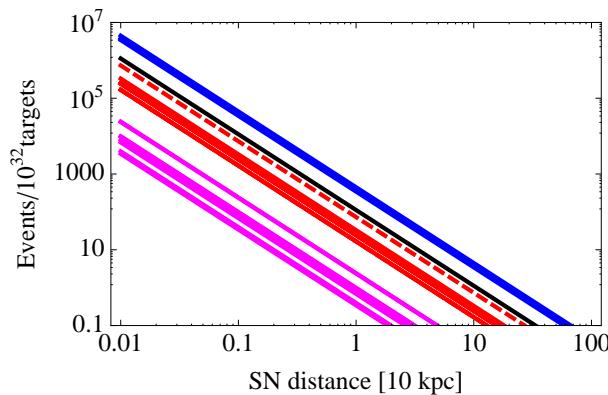
### 4. Conclusions

We have summarized the main features of the interaction channels for supernova neutrinos in massive liquid scintillators. Fig. 9 reports the predicted rate with and without oscillations (normal and inverted hierarchy) against the detector-supernova distance. A galactic supernova will have a distance between 1 and 20 kpc. Fig. 9 shows that present liquid scintillator detectors



**Figure 8.** Regeneration effect due to neutrino travelling through the earth. Dotted line: no oscillations. Dashed line: normal hierarchy. Solid thick line: neutrino travelling through the mantle of the earth.

will observe about 100-400 events for a 10 kpc supernova. The golden channel for supernova neutrinos in liquid scintillators is the inverse-beta decay. The neutrino-proton elastic scattering offers a great opportunity for high purity liquid scintillators as discussed in the text.



**Figure 9.** Rate expected for supernova neutrinos in massive underground detectors against the source-earth distance. From top to bottom: inverse-beta decay; neutrino-proton elastic scattering; neutral current on  $^{12}\text{C}$ ; charged current on  $^{12}\text{C}$ ; neutrino-electron elastic scattering.

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