Status of supernova neutrino detectors

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Abstract. Supernova neutrino observatories currently running are water Cherenkov or scintillator detectors. They differ in technique and performance. These differences have been analyzed and main characteristics of each detector outlined: energy threshold and resolution, pointing capability, duty cycle and number of events expected from a core collapse supernova. Some of these detectors are involved in the Supernova Early Warning System, a network of neutrino observatories dedicated to the prompt recognition of a core collapse supernova in the Galaxy.

Supernova neutrino observatories, presently running, are water Cherenkov and scintillator detectors. Inside these two families there are important differences. Scintillator detectors can be divided into: single volumes (like KamLAND, Borexino and, in the next future, SNO+) and modulars (like Baksan and LVD). They differ in performance, sensitivity and finally interaction channels. Water Cherenkov detectors show, among them, even more evident differences. Super-K and IceCube represent two different ways of detecting SN neutrinos observing Cherenkov light in water. Most of these detectors participate to the Supernovae Early Warning System (SNEWS) [1], 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. To participate to the network, each detector must be able to disentangle a SN neutrino candidate signal by itself, i.e., independently from any other observation. This forces different experiments to develop peculiar strategies for achieving this goal.

In this work I will summarize the main characteristics of detectors concerning SN neutrinos, i.e., number of expected interactions, duty cycle, sensitivity to different neutrino flavors, energy resolution, pointing capability.

The sensitivity of a SN neutrino detector, for example in terms of maximum observable distance, is proportional to the number of detected interactions over the background fluctuations. The expected signal, and the corresponding background, both depend on astrophysical parameters and neutrino properties which are only partially known. All the running SN neutrino detectors, having hydrogenate targets, exploit the inverse beta decay (IBD) interaction of $\bar{\nu}_e$ with free protons, $\bar{\nu}_e + p \rightarrow n + e^+$, to detect SN neutrinos. IBD is definitely the favorite interaction channel in this kind of detectors and in all SN models which predict the emission of neutrinos of all flavors. Moreover the detectors active in occasion of SN1987A were water and scintillator detectors and almost all the interactions detected in that occasion are thought to be IBD. See [2] and references therein for a detailed analysis.

The importance to have different kind of detectors, based on liquid Argon target [3] which has an excellent potential for $\nu_e$ tagging, or on Lead [4], to have a good sensitivity to neutrino flavors other than $\bar{\nu}_e$ is well known. The decommissioning of SNO in 2006 [5], with its unique sensitivity...
to \( \nu_e, \bar{\nu}_e \) and neutral currents, left an unrecouped lack.

The number of IBD interactions detected during an interval of duration \( \delta t \) from the beginning of the collapse can be expressed as:

\[
N_{IBD} = N_H \int_0^{\delta t} dt \int_0^\infty dE\bar{\nu}_e \Phi(E\bar{\nu}_e, t) \cdot \sigma(E\bar{\nu}_e) \cdot \epsilon(E\bar{\nu}_e),
\]

(1)

where \( N_H \) is the number of free protons, \( \Phi \) is the flux of electron antineutrinos, \( \sigma \) the IBD cross section, and \( \epsilon \) the detection efficiency. The number of events expected from a core collapse SN calculated by different models can differ up to a factor two, nevertheless the ratio among the number of events detected by different experiment, through the IBD channel, can be established with a much smaller uncertainty. The detection of a big discrepancy from the expected ratio would indicate a problem in our understanding of the physics of the process. Detection efficiency \( \epsilon(E\bar{\nu}_e) \), and target mass, \( N_H \), are known characteristics of each detector.

Table 1 lists running SN neutrino detectors and their characteristics. The number of IBD events expected from a SN (1987A-like) at 10 kpc is calculated assuming 200 positrons events per kiloton of water target mass, disregarding effects due to different energy thresholds because all modern detectors have a nearly saturated efficiency at \( E_{e^+} = 10 \) MeV and because the contribution due to \( e^+ \) with lower energies is expected to be small 1 (a different approach is needed for Icecube).

| detector            | technique  | mass kton | \( N_{e^+}^{IBD} \) at 10kpc | \( E_{th} \) MeV | \( \sigma_E/E \)MeV | point | duty |
|---------------------|------------|-----------|-------------------------------|------------------|---------------------|-------|------|
| IceCube[6]          | long string| 120 \( \frac{E_{e^+}}{MeV} \) | 300000                       | —                | —                   | n     | —    |
| SK[7]               | H2O Ch.    | 22.5(50)  | 4500(10000)                   | 7.0              | 15%                 | y     | 89%  |
| LVD[8]              | Sc. mod.   | 1.0       | 255                           | 4.0              | 15%                 | n     | 99%  |
| KamLAND[9]          | Sc. vol.   | 1.0       | 255                           | 0.35             | 2%                  | n     | 79%  |
| Borexino[10]        | Sc. vol.   | 0.3       | 75                            | 0.2              | 1.5%                | n     | 75%  |
| Baksan[11]          | Sc. mod.   | 0.13(0.33)| 35(85)                        | 8.0              | 25%                 | n     | 85%  |

It is important to notice that:

(i) The only reason to have different \( \Phi \) at different detectors is the Earth matter oscillation effect. It produces a decrease in the number of detected neutrinos for particular neutrino energy, it is quite weak (depending on the value of \( \Delta m^2_{sol} \) and on the ratio \( T_{\nu_e}/T_{\bar{\nu}_e} \)) and, if the position of the source is known, can be calculated (see for example [12]).

(ii) SuperK is the only one with pointing capabilities, through the \( (\nu^-_i + e^- \rightarrow \nu^-_i + e^-) \) scattering which represents \( \sim 5\% \) of IBD interactions.

(iii) For IceCube, whose effective volume is a function of \( E_{e^+} \), I assumed \( E_{\bar{\nu}_e} = 14 \) MeV. The huge number of interactions must be compared with an important background counting rate. This implies a sensitivity of "only" \( 5\sigma \) at 50 kpc. IceCube cannot distinguish among neutrino flavors nor measuring positron energy, nevertheless, for a Galactic SN, it will furnish a light curve out of reach for the other detector.

1 The visible energy is \( E_{\nu} \sim E_{\nu_e} - \Delta \) in Cherenkov detectors and \( E_{\nu} \sim E_{\bar{\nu}_e} - \Delta + 2m_e c^2 \) in scintillator ones. The ratio between the number of free protons per ton is \( N_{H_2O}/N_{C_6H_2N} = 0.78 \).
(iv) Borexino and KamLAND have a high energy resolution and can reach very low energy thresholds because of their very good light collection. They can easily recognize different interactions and, above all, they are sensitive to the $(\nu_\mu + p \rightarrow (\nu_\mu + p)$ scattering whose number, mainly sensitive to the emission temperature of $\nu_\mu$ and $\nu_\tau$, can be comparable with the number of IBD interactions [13].

(v) Baksan and LVD started their data taking in 1980 and 1992 respectively and they give the most stringent limits to the core collapse SN rate in the Galaxy, even if the capability of Baksan to observe the entire Galaxy, in the present configuration and in the absence of any other signal, is controversial. Modular detectors can be easily operated for a long time with duty cycles near 100%. Independent modules can be treated as independent detectors and the frequency of their coincidences, during a relatively large time window (10-20 sec) can be described by Poisson statistics.

Experiments in bold type in the table are, at present, involved in the SNEWS [14]. Each of them has elaborated its own strategy to disentangle a SN neutrino candidate from the background. To be admitted to the network each detector must keep its average alarm rate lower than a threshold value that is, at present, 1 alarm every 10 days. This relatively high allowed frequency maximizes the detector sensitivity to weak signals, nevertheless it is low enough to keep the accidental two-fold coincidence rate, in a time window of 10 s, lower than one every 100 years. This threshold rate will be modified when the number of detectors involved in the network will increase. SuperK, LVD and SNO have been involved since the very beginning and performed a high rate test in 2001 [1]. IceCube now supersedes AMANDA that had been participating to the network since 2004 and Borexino is in a test phase. LVD and Borexino, because they are host in the same underground laboratory, are not considered, by SNEWS, as completely independent. The neutrino signal, in a core collapse supernova event, precedes the electromagnetic one by hours therefore present detectors can behave as trigger for electromagnetic and gravitational wave detectors [15]. A few galactic supernova are expected per century and SNEWS can provide an alert within minutes. We are patient.

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