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Improved method for the detection of low-energy astrophysical neutrinos bursts

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Abstract. In this paper we describe an improved method for the search of astrophysical bursts of low-energy neutrinos. We use the different temporal behaviour describing impulsive signal with respect to the flat temporal expectation for background events. We show that this approach strongly reduces the misidentification probability without decreasing the detection probability. In other words, this method allows to neutrino detectors to work at lower threshold with the same statistical confidence.

1. Introduction

Core-Collapse Supernovae (CCSNe) [1] represent the final explosive fase of massive stars and the detection of a galactic event could be the unique opportunity for us to grasp the physical mechanism driving the final explosion of the structure. On the other hand "Failed" Supernovae [2] are collapsing stars that fail to explode forming an inner black hole. The lack of the final explosion make these sources optically silent and, at the present, have never been directly observed. Finally, Quark Novae [3], are expected when a neutron star suddenly converts into a quark star. Their existence is strongly related to the fundamental state of the matter and their detection could provide the first clear evidence of the presence of strange matter in the universe.

A common signature for all these catastrophic astrophysical phenomena is expected to be an impulsive (~ 10 seconds) emission of low-energy, (~ 10 MeV), neutrinos [4, 5, 6]. Despite the large amount of total energy ($\sim 10^{53}$ ergs) released in neutrinos, when the source distance increases and/or the average energy of emitted neutrinos decreases the signal statistics drops and the identification of these astrophysical bursts embedded into the detector noise could be challenging.

In this paper, we improve the detectors capability to disentangle real astrophysical bursts of low-energy neutrinos from background signals. This powerful method exploits the different temporal structure expected for an astrophysical burst with respect to background fluctuations that are near uniformly distributed in a time window. This characteristic, described with a new parameter, can be used as an additional degree of freedom that added to the statistical requirement improves our capability to identify real signals, allowing the detection of weaker/far away astrophysical sources.



2. Emission Model

For all the astrophysical sources we are interested in, we assume that the total energy radiated in neutrinos is $\mathcal{E} = 3 \times 10^{53}$ erg. We consider a very general description of an astrophysical burst of low-energy neutrinos characterised by the following temporal evolution:

$$f(t) = (1 - \exp(-t/\tau_1)) \exp(-t/\tau_2), \quad (1)$$

where $\tau_1 = (10 - 100)$ ms is the rising time and $\tau_2 \geq 1$ s represents the decaying time of the signal.

As spectral shape for the signal we assume quasi-thermal spectra and the neutrino fluence, differential in the neutrino energy E , is described by

$$\Phi_i^0 = \frac{\mathcal{E}_i}{4\pi D^2} \times \frac{E^\alpha e^{-E/T_i}}{T_i^{\alpha+2} \Gamma(\alpha+2)} \quad i = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau, \quad (2)$$

where the energy radiated in each specie is $\mathcal{E}_i = \mathcal{E}/6$ due to the equipartition hypothesis, Γ is the Gamma function and the ‘temperature’ is $T_i = \langle E_i \rangle / (\alpha + 1)$. The average energy per flavour is $\langle E_i \rangle$ and the parameter $\alpha = 3$ represents a mild deviation from a thermal distribution. As average energies we set $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 12$ MeV and non-electronic temperature 30% higher than the one of $\bar{\nu}_e$. All these values are compatible with SN1987A[7]. As interaction channel we consider the main interaction channel, i.e., the inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$. Due to neutrino oscillations the $\bar{\nu}_e$ fluence at the detector is an admixture of the unoscillated flavour fluences at the source: $\Phi_{\bar{\nu}_e}^0 = P\Phi_{\bar{\nu}_e}^0 + (1 - P)\Phi_x^0$, where x indicates the non-electronic flavours and P is the survival probability for the $\bar{\nu}_e$. Depending on the neutrinos mass hierarchy, this probability can be $P = 0$ for Inverted Hierarchy (IH) or $P \simeq 0.7$ for Normal Hierarchy (NH).

The expected number of IBD interactions is $S(E_\nu, D) = N_p \sigma_{\bar{\nu}_e p}(E_\nu) \Phi_{\bar{\nu}_e}(E_\nu, D) \epsilon(E_{vis})$, where D is the source distance, N_p is the number of target protons within the detector, $\sigma_{\bar{\nu}_e p}$ [8] is the process cross section and ϵ is the detector efficiency as a function of the visible energy E_{vis} . The visible energy is the portion of interaction energy released inside the detector that can be observed; for the detectors considered in this paper, it is the energy converted in light inside the sensitive volume. We show our results for the NH case with $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV.

3. Method

The aim of this paper is to show an improved way to discriminate astrophysical burst of low-energy neutrinos from accidental burst of events due to background. For this reason background knowledge and characterization is fundamental to demonstrate the potential of this method. Low-energy neutrinos detectors at the present on data-taking like Super Kamiokande[9], LVD[11], Borexino[12] and KamLAND[13] provide all the information needed to perform this study and results are reported for these detectors both considering that they are working alone and by exploiting combined coincident search.

In all the considered detectors the search of astrophysical bursts of low-energy ν is based on the definition of clusters of events and then by a statistical selection of the most significant clusters. Following [15] we define a cluster as the group of the events contained in consecutive time windows of $w = 20$ seconds. Each cluster is characterised by its multiplicity m_i and its time duration Δt_i , defined as the time difference among the first and the last event detected inside the window. In order to increase the detection probability this search is performed one more time by shifting the consecutive time windows of 10 seconds with respect to the first search, for more details see [15].

A Monte Carlo simulation of 10 years of data-taking has been performed in order to reproduce the background fluctuations of each detector according to the parameters (frequencies and energy thresholds) reported in Tab.1.

For the observed background clusters of events we calculate its imitation frequency $f_i^{im}(\text{day}^{-1})$, i.e. how many times in a day background events produce a cluster with the same multiplicity. In the following we set as working threshold for this statistical cut the value $f_i^{im} \leq 1/\text{day}$ in order to test the new method to discriminate signal from background. Then we simulate the signals expected in each neutrino detector by assuming the temporal behaviour in Eq. 1 and the energy spectra in Eq.2. The Monte Carlo extraction for the signals are performed considering different source distances D , in the range $8.5 - 500$ kpc. As further step, simulated signals are randomly injected inside the background. Once that clusters are obtained following the previous procedure only clusters with $f_i^{im} < 1/\text{day}$ are selected. For each cluster we define the parameter, ξ_i as the ratio between the cluster multiplicity and the cluster duration:

$$\xi_i = \frac{m_i}{\Delta t_i}. \quad (3)$$

As a function of ξ we study the distributions of pure background clusters and background plus signal clusters in term of normalised Probability Density Functions (PDF). In Panel (a) of Fig 1 we show the result obtained for SuperK detector. The distribution of clusters due to pure

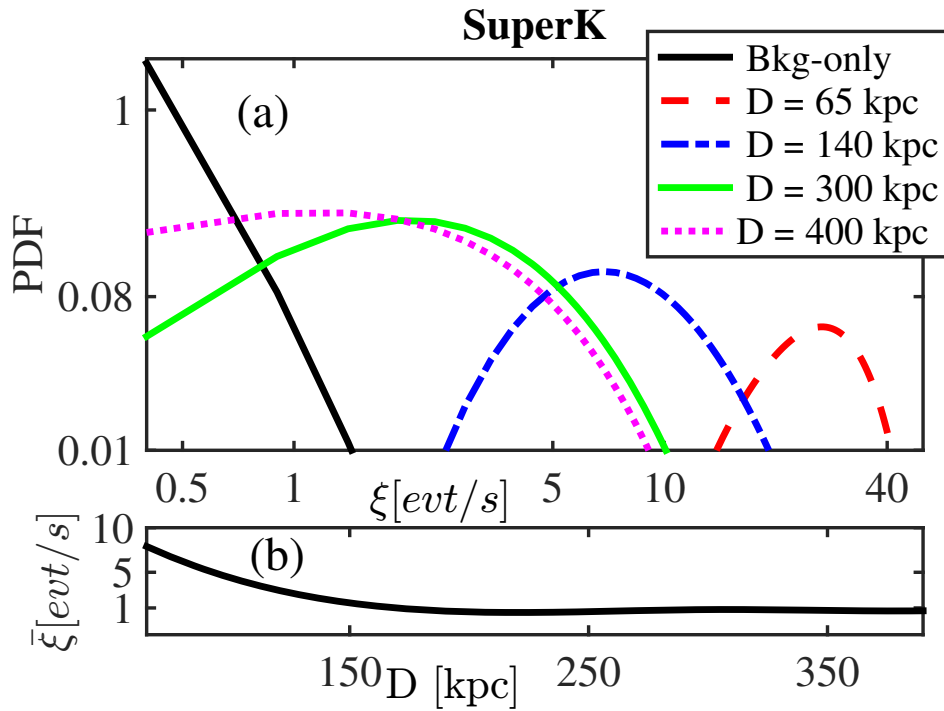


Figure 1. Panel (a): Probability density functions for background plus signal clusters as functions of the ξ parameter and for different distances in the case of SuperK detector. The black solid line shows the PDF for pure background clusters; Panel (b): The optimal cut value for the ξ parameter, $\bar{\xi}(D)$, as a function of the source distance D for SuperK detector.

background events is reported with a black solid line and is characterised by very small values of the ξ parameter as expected for events with a temporal uniform distribution, i.e., $\Delta t_i \rightarrow w$ seconds. On the other hand, clusters where also an astrophysical signal is present show a PDF shifted at higher values of the ξ axis, as expected for clusters with events that cumulate faster in time $\Delta t_i < 20$ seconds. For any fixed source distance the PDF is different and the Panel (a) of Fig.1 we show with different color the case of $D=65, 140, 300$ and 400 kpc as expected in

SuperK. For any fixed source distance the PDF is different and a different optimal cut value for the ξ parameter can be defined in order to separate background and signal distributions. By performing several simulations we define the function $\bar{\xi}(D)$, reported in Panel (b) of Fig.1 for the case of SuperK. Finally, we define as optimal value of the cut parameter $\bar{\xi}_X$ the smaller one allowing a clear separation between background and signal PDFs. Following this prescription, in the last column of Tab.1, we report the optimal cut parameters found for all the detectors considered.

So that, we add as new cut on the previous selected clusters, with $f_i^{im} < 1/\text{day}$, the condition $\xi_i \geq \bar{\xi}_X$ and we investigate the impact of this on the detection probability, η , and on the misidentification probability ζ . The detection probability is defined as the ratio between the number of signal clusters recovered by the analysis that survive after the cuts and the number of signal clusters that was initially injected into the background. In a similar manner the misidentification probability, ζ , is obtained as the fraction of background clusters that survive all the cuts over the total number of clusters observed.

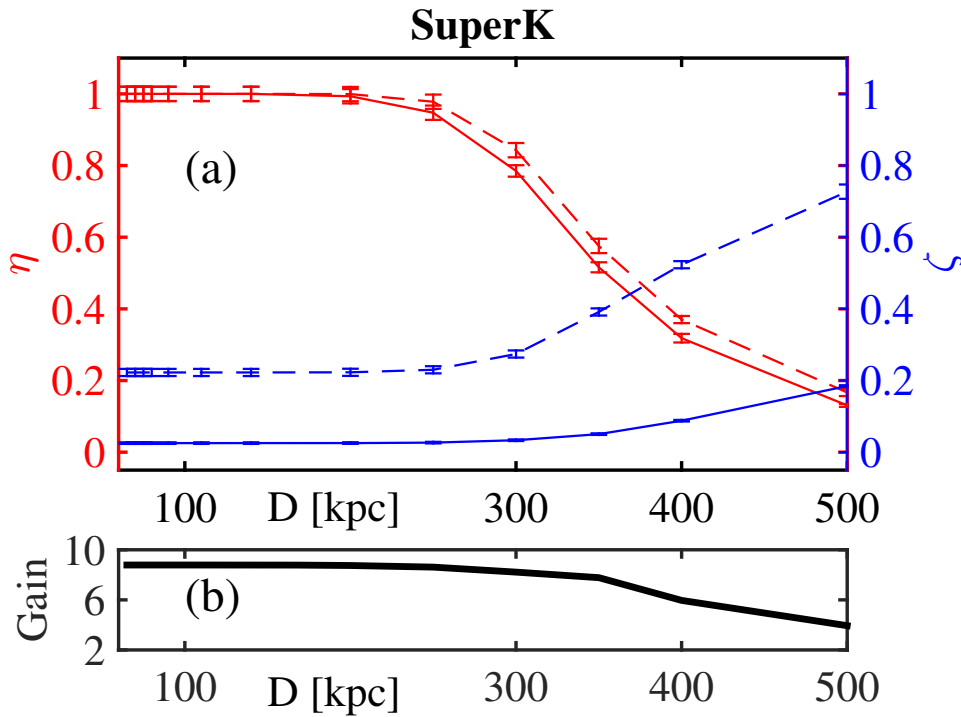


Figure 2. Panel (a): Red lines show the detection probability curves, η , whereas blue lines show the misidentification probability curves, ζ , as a function of the source distance D for SuperK detector working at $f_i^{im} \leq 1/\text{day}$. Solid (Dashed) lines are obtained by following the new proposed (standard) method for background reduction. Panel (b): The gain factor for SuperK as defined in the text versus the source distance D .

As a leading example we apply our search procedure to SuperK detector and we compare the detection probability obtained with the new procedure with respect to the standard procedure only based on statistical cut. To show the improvement provided by our method we plot in Panel (a) of Fig.2 the detection efficiency η with red lines and the misidentification probability ζ with blue lines. In particular dashed lines are obtained by using the standard procedure only based on statistical cut as described above while the solid lines are obtained by applying our additional selection criterium. As evident by the picture the efficiency is unchanged till a distance of ~ 200

kpc while the misidentification that was around a 23% by using the standard procedure drops to very small value around 3% by applying the $\bar{\xi}$ cut.

Detector	M(kton)	E_{thr} (MeV)	f_{bkg} (Hz)	ξ (Hz)	$\bar{D}$ (kpc)	G
Borexino	0.3	1	0.048	0.65	20	6.9
SuperK	22.5	7	0.012	0.72	200	8.9
KamLAND	1	1	0.015	0.77	50	13.4
LVD	1	10	0.028	0.72	40	14.0

Table 1. Columns in order show: sensitive detector mass in kton; energy threshold considered for the analysis in MeV; average background frequency in Hz[9, 11, 12, 13]; value for the $\bar{\xi}$ parameter that maximise the signal to noise ratio, as described in the text; maximal distance $\bar{D}$ without efficiency loss after the new cut; gain factor obtained by using the new proposed method.

In Tab.1 we show the results obtained for all the detectors considered. In particular, the maximal distance $\bar{D}$ (kpc) for which no efficiency loss is due to the additional $\bar{\xi}$ cut and the corresponding gain, $G = \zeta/\zeta'$, obtained for such a distance, obtained as the ratio between the misidentification probability before and after the $\bar{\xi}$ cut. This gain factor is reported in the lower panel of Fig.2 for the SuperK case study.

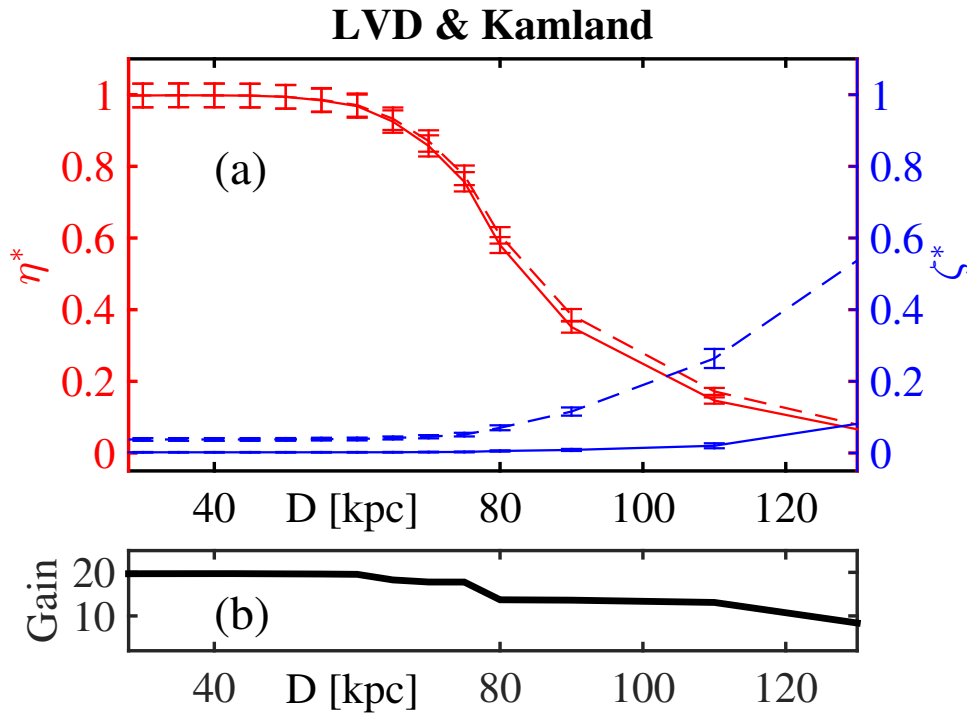


Figure 3. Panel (a): Red lines show the detection probability η^* whereas blue lines show the misidentification probability ζ^* for the network LVD & Kamland. Solid (Dashed) lines are obtained by following the new proposed (standard) method for background reduction. Panel (b): The gain factor for the network LVD & Kamland as defined in the text as a function of the source distance D .

When two or more detectors work together, the new method proposed can be extended. In

this case, in order to construct a list of candidate clusters a further step is required, i.e. the temporal coincidence among clusters in different detectors within a time window that we assume to be $w_c = 10$ seconds [14]. In this case the procedure for the clusters definition is the same as described in the previous section and astrophysical signals are injected taking into account the time of flight between the detectors in order to simulate a real astrophysical event. The next step is the definition of the coincidences among the detectors considered. Once that coincidences were found, we require that the product of the ξ_X of coincident clusters is greater than the global cut value:

$$\bar{\xi}^* = \sqrt[N]{\prod_{X=1}^N \bar{\xi}_X}, \quad (4)$$

where N is the number of detectors in the network. The sensitivity of the neutrino network can be obtained by using extended definition of the detection efficiency η^* , i.e. the number of astrophysical clusters passing the statistical cut on f_{im}^X that are found in coincidence and are characterised by a global $\bar{\xi}^*$ greater than the cut value defined in Eq.4 over the total injected signals. In a similar manner the network definition of the misidentification probability ζ^* become the ratio among the background coincidences and the total number of coincidences found. As a leading example we show the case of LVD and Kamland working together. The detection efficiency and the misidentification probability of this network are showed in the upper panel of Fig.3. As in the previous plot dashed lines represent the old method based on statistical cut plus temporal coincidence search, while solid lines show the same quantities obtained by adding the $\bar{\xi}^*$ cut described above.

In particular the misidentification probability nearly constant until 75 kpc, drops from a value around 4% to a value around 0.2%, in other words the gain factor obtained in this distance range is around ~ 20 and is reported in the lower panel of Fig.3 for different distances. This reduction of the misidentification can be also converted in term of a reduction of the FAR for the network. In other word, a network like LVD plus Kamland working at a FAR of 0.001/day(0.365/year) with the inclusion of our method based on the ξ^* cut can reach the same background level of the same network working at the SNEWS threshold of 1/1000 years where only the statistical selection is applied.

We apply this extended procedure to all the possible sub-networks of detectors possible including LVD, Borexino, LVD, Kamland, and SK. In any case the improvement obtained is of the same order, indeed also for the cases of combined search between LVD and Borexino or Kamland and Borexino the gain obtained is of a factor ~ 19 , however with a reduced distance $\bar{D} \sim 50$ kpc due to the lower sensitivity of Borexino.

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