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Update on the search for supernova neutrino bursts with the LVD experiment

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The Large Volume Detector (LVD) at INFN Gran Sasso National Laboratory (Italy) is a 1 kt liquid scintillator neutrino observatory, mainly designed to study neutrinos from gravitational stellar collapses. It has full efficiency for the detection of supernova neutrino bursts in the whole Galaxy. In this contribution we summarize the results of the last run, lasting from 2014, January 1st to 2023, March 3rd for a total live time of 3338 days. No supernova neutrino burst has been observed in this data set. Considering all previously published results since 1992 for a total live-time of 10673 days, the upper limit on the supernova rate up to distances of 25 kpc is 0.078 y^{-1} at 90% c.l..

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1. Introduction

Gravitational Stellar Collapses (GSC) are astrophysical events of great interest. Because of the complexity of the problem, the modelling of the physical processes is still in evolution, but it is in general accepted that the role of neutrinos is critical to allow the supernova to form out of a collapse [1].
The detection of the neutrino signal from the SN 1987A marked the beginning of a new era in neutrino astrophysics (e.g. in [2–4]) and, in spite of some unresolved controversies [5], paved the way for *Neutrino Astronomy*.
At the time of next supernova in our Galaxy the correlated neutrino burst will be eventually detected by different detectors. Such rare event is expected to happen in the Galaxy every 30-50 years [6] and therefore enforces to set up detectors which last for decades with a very high duty cycle.
Actually, since light can be partially or totally absorbed by dust in the Galactic plane while neutrinos are not (see e.g. [7]), large long-term neutrino detectors are the most suited ones to observe the Galaxy and search for GSC. Neutrino detectors are also sensitive to collapsing objects that fails to explode becoming black holes, the so-called failed supernovae (fSN). Those are expected to emit a neutrino signal more intense [8], although shorter in time, than exploding GSC.

2. The LVD detector

The Large Volume Detector (LVD) is a 1 kt liquid scintillator detector located underground (minimum depth 3000 m w.e.) at INFN Gran Sasso National Laboratory (Italy). The experiment consists of an array of 840 scintillator counters, 1.5 m^3 each, viewed from the top by three photomultipliers (PMTs) and arranged in a modular geometry [9]. This modularity allows LVD to achieve a very high duty cycle, which is essential in the search of unpredictable sporadic events like supernova neutrino bursts. Failures involving one or more counters do not affect, in general, other counters. The detector maintenance can be done during data acquisition by stopping only the part that needs to be maintained, even down to a single counter. This peculiarity allows a *dynamic* active mass M_{act} and a high duty cycle. After a short commissioning phase, the experiment has been taking data since 1992, June 9th, with its active mass progressively increasing from 300 t to 1000 t, which was reached at the time of building phase completion in January 2001. Duty cycle and active mass along the experiment life, up to 2023, March 3rd are shown in Fig. 1.

Thanks to the long dataset and high duty cycle, LVD has been able to study other physics topics beyond the main task of GSC neutrinos detection. In particular, a detailed study of the modulation of the atmospheric muons detected underground (~TeV energy) has been performed analysing the longest muon data series (1994-2017) ever achieved by an underground detector [10, 11].

3. Expected neutrino interactions in LVD

Neutrinos can be detected in LVD through charged current (CC) and neutral current (NC) interactions on proton, carbon nuclei and electrons of the liquid scintillator but also on the iron nuclei of the support structure (850 t). In the latter case the products of interactions in iron can

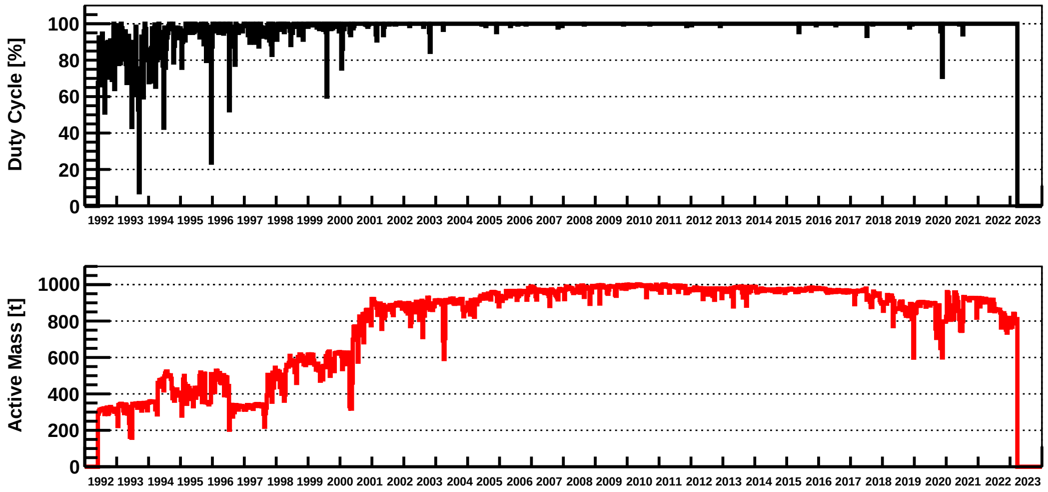

Figure 1: LVD duty cycle and active mass as a function of time from 1992, June 9th to 2023, March 3rd.

eventually reach the scintillator and be detected [12]. The total target thus consists of $8.3 \cdot 10^{31}$ free protons, $4.3 \cdot 10^{31}$ C nuclei, $3.4 \cdot 10^{32}$ electrons in the scintillator and of $9.7 \cdot 10^{30}$ Fe nuclei. The main interaction channel in LVD in case of a supernova neutrino burst is the Inverse Beta Decay (IBD), as it can be seen in Table 1, where all other relevant neutrino interaction channels are also shown. Given the relevance of the IBD, the LVD trigger has been optimized for the detection of both products of this interaction, namely the positron and the neutron. Each PMT is thus discriminated at two different threshold levels, the higher one ($\mathcal{E}_{\mathrm{H}} \simeq 4$ MeV in the present settings) is also the main trigger condition for the detector array. The lower one ($\mathcal{E}_{\mathrm{L}} \simeq 0.5$ MeV) is in turn active only in a 1 ms time-window following the trigger, allowing the detection of (n, p) captures, the marker of a possible IBD interaction in the detector. Once a trigger is identified, the charge and time of the three summed PMTs signals are stored in a memory buffer. One millisecond after the trigger, all memory buffers are read out.

	ν interaction channel	E_ν threshold	%
1	$\bar{\nu}_{\mathrm{e}} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$	(1.8 MeV)	(88%)
2	$\nu_{\mathrm{e}} + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N} + \mathrm{e}^-$	(17.3 MeV)	(1.5%)
3	$\bar{\nu}_{\mathrm{e}} + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + \mathrm{e}^+$	(14.4 MeV)	(1.0%)
4	$\nu_{\mathrm{i}} + {}^{12}\mathrm{C} \rightarrow \nu_{\mathrm{i}} + {}^{12}\mathrm{C}^* + \gamma$	(15.1 MeV)	(2.0%)
5	$\nu_{\mathrm{i}} + \mathrm{e}^- \rightarrow \nu_{\mathrm{i}} + \mathrm{e}^-$	(-)	(3.0%)
6	$\nu_{\mathrm{e}} + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Co}^* + \mathrm{e}^-$	(10. MeV)	(3.0%)
7	$\bar{\nu}_{\mathrm{e}} + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Mn} + \mathrm{e}^+$	(12.5 MeV)	(0.5%)
8	$\nu_{\mathrm{i}} + {}^{56}\mathrm{Fe} \rightarrow \nu_{\mathrm{i}} + {}^{56}\mathrm{Fe}^* + \gamma$	(15. MeV)	(2.0%)

Table 1: Expected interaction channels for a supernova neutrino burst in LVD. The last column shows the relative fractions of events for any interaction channel. The parametric emission model [13] is assumed.

The number of detected events in LVD for a supernova neutrino burst has been evaluated via a parameterized model based on a maximum likelihood procedure on the data from SN 1987A [13]. The resulting average $\bar{\nu}_e$ energy is $\bar{\mathrm{E}}_{\bar{\nu}_\mathrm{e}}$ = 14 MeV, being $\mathrm{E_b} = 2.4 \cdot 10^{53}$ erg the total radiated energy. Energy equipartition and normal mass hierarchy for neutrino oscillations are also assumed. At a reference distance D = 10 kpc for the GSC, we found that a total of 300 events (260 at $\mathrm{E}_\nu \geq 10$ MeV) are expected in LVD with a 1 kt active mass, 88% of which are due to IBD (see details in [14]).

We have also evaluated the expected number of detected neutrino in LVD in the case of a fSN, referring to the model in [8]. A total of 500 events at $\mathrm{E}_\nu \geq 10$ MeV in 0.36 s is expected at D = 10 kpc in the most conservative scenario.

4. Search for neutrino bursts

LVD science runs started in June 1992 and, since then, the results of the search for supernova neutrino bursts with LVD have been periodically reported at ICRCs (see [15] and references therein) and discussed in detail in a paper [16] which covers data from 1992 to 2013. Here we focus on the results of the analysis of the last run from 2014, January 1st to 2023, March 3rd for a total live-time of 3338 days, which represents a duty cycle of 99.7%. A total of 2.96 10^9 triggers are included in the data set, but they get reduced to 7003576 in the [10-100] MeV energy range after muon rejection and quality cuts are applied. Table 2 summarizes the main features of the last run: average trigger rates before and after selections, active mass, total exposure and livetime.

	$\mathrm{R_{tot}}$ $[\mathrm{s}^{-1} \cdot \mathrm{t}^{-1} \cdot 10^{-4}]$	$\mathrm{R_{10}}(\mathrm{E} \geq 10\ \mathrm{MeV})$ $[\mathrm{s}^{-1} \cdot \mathrm{t}^{-1} \cdot 10^{-4}]$	$\mathrm{R_L}(\mathrm{E} \geq 0.5\ \mathrm{MeV})$ $[\mathrm{s}^{-1} \cdot \mathrm{t}^{-1}]$	$\bar{\mathrm{M}}_{\mathrm{act}}$ [t]	Exposure $[\mathrm{t} \cdot \mathrm{y}]$	live time [days]	live time ($\mathrm{M} \geq 300$ t) [days]
Last run	117	0.28	279	880	8048	3339	3338

Table 2: Main features of the data set from the last run.

As it is apparent from Fig. 2, the total counting rate f results to be quite stable after the quality selections are applied. The distribution of time delays between consecutive triggers is shown in Fig. 3, normalized to a reference background rate ($\delta t_{\mathrm{norm}} = \delta t \cdot f / f_{\mathrm{ref}}$, being $f_{\mathrm{ref}} = 0.03\ \mathrm{s}^{-1}$ the typical average rate for the full LVD detector in the [10-100] MeV range) to take into account the variable active mass configurations (Fig. 1). The LVD events behave as a stochastic time series well described by the Poisson statistics, as shown by the exponential fit in Fig. 3.

The search for supernova neutrino bursts in LVD data is based on a purely statistical procedure. The method used in this analysis is described in detail in [17] and it is summarized here. It consists of a two-step process.

In the first step, we analyze the entire time series to search for clusters of events. The rationale of the search is that every *n-th* event could be the first of a possible neutrino burst. As we do not know a priori the duration of the burst, we consider all clusters formed by the *n-th* event and its successive ones. Namely, the *n-th* and the *(n+1)-th* ones define a cluster of multiplicity $m = 2$; the *n-th, (n+1)-th, (n+2)-th* ones define another cluster of $m = 3$, and so on. The duration of each cluster is given by the time difference Δt between the first event *n-th* and the last one of each

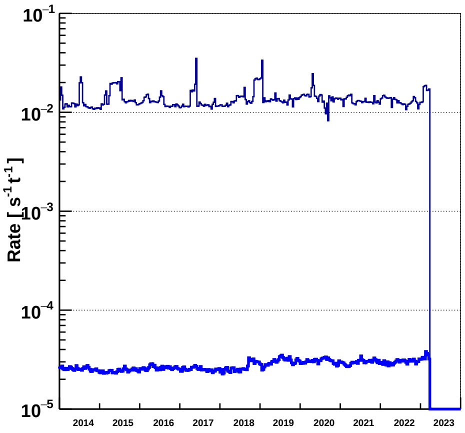

Figure 2: LVD counting rate as a function of time in the last run: top (thin) and bottom (thick) lines show respectively the total rate before and after quality and energy selection cuts are applied.

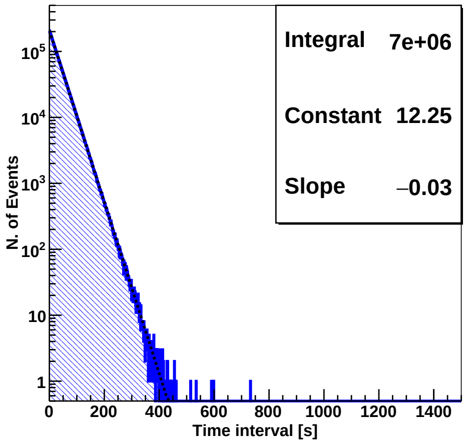

Figure 3: Distribution of normalized time delay between consecutive triggers of the last run. The exponential fit shows that the stochastic time series is in good agreement with the expected Poisson statistics.

sequence up to a maximum value of $\Delta t_{max} = 100$ s. The analysis is then applied to the *(n+1)-th* event, and iteratively to all LVD events. Each cluster is characterized by its multiplicity m_i and duration Δt_i . The advantage of the described analysis is that it is unbiased with respect to the duration of the possible neutrino burst, which is unknown a priori. The choice of $\Delta t_{max} = 100$ s is very conservative as it well exceeds the expected duration of a neutrino burst from GSC (tens of seconds) and even more from fSN (ms-s time scale).

The second step of the process consists in determining if one or more among the detected clusters are neutrino burst candidates. For this purpose, we calculate for each cluster the imitation frequency F_{im_i}. This quantity represents the frequency with which background fluctuations can produce, by chance, clusters with multiplicity $m \geq m_i$ and duration Δt_i. As shown in [17], it depends on $(m_i, \Delta t_i)$, on the background frequency, f_{bk} and on the maximum cluster duration chosen for the analysis, Δt_{max}, and can be written as:

$$F_{im_i} = f_{bk}^2 \Delta t_{max} \sum_{k \geq m_i - 2} P(k, f_{bk} \Delta t_i) \tag{1}$$

where $P(k, f_{bk}\Delta t_i)$ is the Poisson probability to have k events in the time window Δt_i if f_{bk} is the background frequency.

Given the long duration of the LVD data set, we choose $F_{im}^{th} = 1/100\ y^{-1}$ as threshold imitation frequency. This means that a cluster $(m_i, \Delta t_i)$ is considered a neutrino burst candidate if:

$$\sum_{k \geq m_i - 2} P(k, f_{bk} \Delta t_i) < \frac{F_{im}^{th}}{f_{bk}^2 \cdot \Delta t_{max}}. \tag{2}$$

The concept of the imitation frequency has a double advantage. From the viewpoint of the search for neutrino bursts, it allows us to define a priori the statistical *significance* of each cluster in terms of the background frequency, in general not constant but actually changing with the detector active mass. Moreover, it allows us to monitor the performance of the search algorithm and the stability of the detector by changing the imitation frequency threshold. Namely, we study the distributions of time differences between consecutive clusters for three different values of imitation frequency ($F_{im} < 1$ day^{-1}, week^{-1}, month^{-1}). Given the limited statistics we get when considering only the current run (455, 71 and 21 clusters detected at $F_{im} < 1$ day^{-1}, week^{-1}, month^{-1} respectively), we perform this study including the data already published for the period 1992-2013 [16]. This results in a total of 1578, 236, 66 clusters for the 3 imitation frequencies, respectively. The distributions of the time differences between consecutive clusters are shown in Fig. 4 for $F_{im} < 1$ day^{-1} (black solid line), $F_{im} < 1$ week^{-1} (green solid line) and $F_{im} < 1$ month^{-1} (blue solid line). The superimposed dotted lines are pure exponential fits to each distribution following the expected Poissonian behaviour. This result shows that the search algorithm and the detector are quite under control over the whole period of data taking.

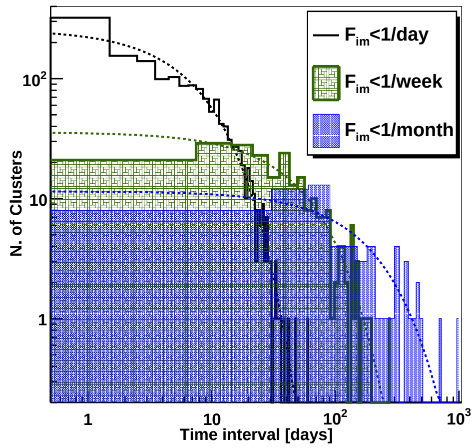

Figure 4: Distribution of time intervals between consecutive clusters (solid lines) fitted by Poisson laws (dashed lines). All data since 1992 have been included here.

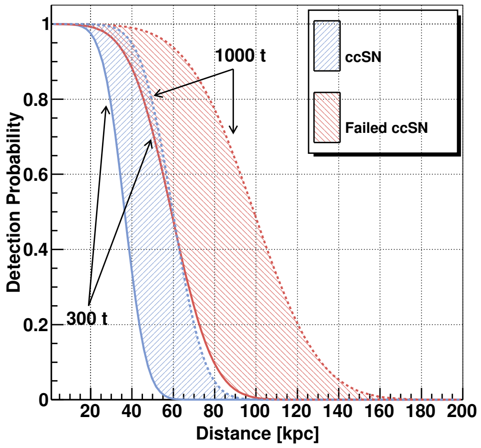

Figure 5: LVD detection probability versus supernova distance for $F_{im} < 1/100$ y^{-1} for both GSC (ccSN) and fSN (Failed ccSN) in the range of minimum (300 t) and maximum (1000 t) active mass.

The neutrino burst detection probability associated to this analysis method is shown in Fig. 5 for $F_{im} < 1/100$ y^{-1} as a function of the distance of the supernova. The blue band corresponds to the case of standard GSC, the solid (dashed) line represents an active mass of 300 (1000) t. The red band evaluates the detection probability in the case of fSN.

We can conclude that LVD is fully efficient to detect GSC and fSN in the whole Galaxy (distances up to 25 kpc) provided the detector active mass is greater than 300 t.

5. Results

A total of 17114385 clusters ($m \geq 2$ and $\Delta t \leq 100$ s) were identified in the last run (3338 days).

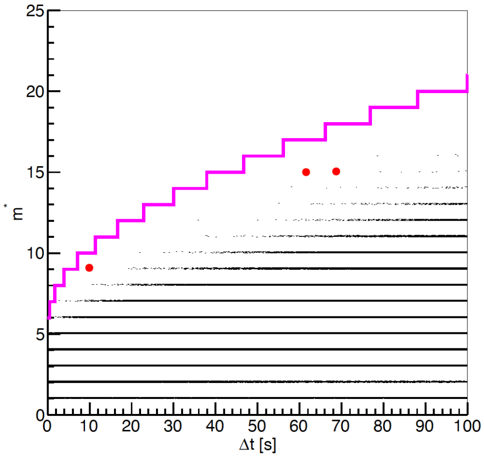

Figure 6: Distribution of detected clusters in the space ($\Delta t, m^*$). Red dots represent clusters with imitation frequency $F_{im} < 1\ y^{-1}$. The purple line corresponds to $F_{im}^{th} = 1/100\ y^{-1}$.

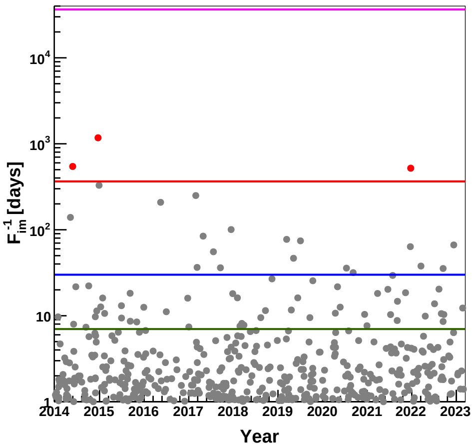

Figure 7: Distributions of detected clusters in time for the present data set. The vertical axis reports F_{im}^{-1}. Red dots represent clusters with imitation frequency $F_{im} < 1\ y^{-1}$. Green, blue, red and purple lines corresponds to $F_{im}^{th} = 1$ week^{-1}, $F_{im}^{th} = 1$ month^{-1}, $F_{im}^{th} = 1\ y^{-1}$, $F_{im}^{th} = 1/100\ y^{-1}$, respectively .

Fig. 6 shows the correlation between the cluster duration, Δt, and the normalized multiplicity, m^*, which takes into account the different instantaneous background rate at time of detection and allows to put all clusters toghether normalized to the reference background rate, f_{ref}. Details on the normalization procedure are discussed in [16]. Fig. 7 shows the inverse of the imitation frequency F_{im}^{-1} of all clusters as a function of time. It is apparent that the occurrence of clusters with different F_{im} is quite uniform. In both figures the purple line marks $F_{im}^{th} = 1/100\ y^{-1}$, i.e., the threshold to consider a cluster as a neutrino burst candidate. No cluster in the whole period was found with $F_{im} < 1/100\ y^{-1}$, and so no neutrino burst candidate is identified. Three clusters have $F_{im} < 1\ y^{-1}$ and their characteristics are reported in Table 3. The most significant cluster has $F_{im}^{-1} = 3.22$ y, with $m = 8$ events and $\Delta t = 9.98$ s. All these three clusters have been also checked in terms of energy spectra and number of low energy signals N_L that may be the signature of the IBD interactions. They are fully compatible with chance coincidence among background signals. We conclude that no evidence is found for GSC or fSN in the whole data-taking period under study. Considering that the total live-time of LVD since the beginning of data taking is 10673 days, the upper limit at 90% c.l. to the rate of GSC and fSN out to 25 kpc is 0.078 y^{-1} .

n.	UTC	M_{act}[t]	$f_{bk}[s^{-1}]$	m	Δt[s]	F_{im}^{-1}[y]	$\bar{E}$[MeV]	N_L
1	2014 25 May 3:54:14.555	959	$2.78 \cdot 10^{-2}$	14	61.56	1.49	22.6	4
2	2014 18 December 20:21:28.787	937	$2.33 \cdot 10^{-2}$	8	9.98	3.22	18.8	3
3	2021 23 December 00:39:00.279	863	$2.55 \cdot 10^{-2}$	14	68.75	1.42	19.0	4

Table 3: Characteristics of clusters with $F_{im} < 1\ y^{-1}$.

6. Conclusions

In this paper we have summarized the results of the search for supernova neutrino bursts performed with LVD over the last run since 2014, January 1st to 2023, March 3rd. Neutrino burst candidates are statistically selected as clusters of events with an imitation frequency $F_{im} < 1/100$ y^{-1} and maximum duration $\Delta t_{max} = 100$ s. This makes our search model-independent, as the duration of a neutrino burst due to a supernova explosion is not known a priori. The knowledge of the background as well as its long-term stability are of essence to correctly calculate the imitation frequency of each cluster. None of the $\sim$ 17 millions clusters has $F_{im} < 1/100$ y^{-1} in the current run. We conclude that no evidence has been found for GSC, or fSN, occurred within 25 kpc during the period of observation. Taking into account all previous data since 1992 for a total livetime of 29.24 y, we set an upper limit on the supernova rate in the Galaxy of 0.078 y^{-1} at 90% c.l.. This is currently the most stringent limit for the observation of supernovae through neutrinos in the entire Galaxy.

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