Abstract: The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory, Italy, is a 1 kt liquid scintillator neutrino observatory mainly designed to study low energy neutrinos from gravitational stellar collapses in the Galaxy. The experiment has been taking data since June 1992, under increasing larger mass configurations. The telescope duty cycle, in the last ten years, has been greater than 99%. We have searched for neutrino bursts analysing LVD data in the last run, from May 1st, 2009 to March 27th, 2011, for a total live time of 696.32 days. The candidates selection acts on a pure statistical basis, and it is followed by a second level analysis in case a candidate is actually found in the first step. We couldn’t find any evidence for neutrino bursts from gravitational stellar collapses over the whole period under study. Considering the null results from the previous runs of data analysis, we conclude that no neutrino burst candidate has been found over 6314 days of live-time, during which LVD has been able to monitor the whole Galaxy. The 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy results to be 0.13 events / year.

Gravitational stellar collapses (GSC) are astrophysical events of great interest. The modeling 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 confirmed detection of the neutrino signal from the SN1987A, which was located in the Large Magellanic Cloud, marked the beginning of a new era in neutrino astrophysics [2, 3, 4] and, in spite of some unresolved controversies [5], opened the way to neutrino astronomy. Even in the lack of a complete theory of the core collapse supernova explosion the correlated neutrino emission is believed to be well established and should be detected with different active detectors at the time next event will occur within the Milky Way boundaries.

All the experiments aiming at the detection of neutrino bursts from core collapse supernovae have to face the extremely low frequency of this events. One core collapse supernova is expected to happen within the borders of the Galaxy every 30-50 years [6]. This implies the ability to set up detectors which last several years with a very high duty cycle. Another crucial point is that, in the absence of others detectable signals, neutrino telescopes must be able to recognize the neutrino burst from the background with very high reliability.

1 The Large Volume Detector (LVD)

The Large Volume Detector (LVD), located in the hall A of the INFN Gran Sasso National Laboratory, Italy, is a neutrino observatory with 1000 tons of liquid scintillator as an active target. The major purpose of LVD is the search for neutrinos from GSC in our Galaxy [7]. The detector consists of an array of 840 scintillator counters, 1.5 m$^3$ each, organized in a compact structure (dimensions $13 \times 23 \times 10$ m$^3$). The whole array is divided in three identical towers with independent power supply, trigger and data acquisition. In turn, each tower consists of 35 modules hosting a cluster of 8 counters. Each counter is viewed from the top by three photomultipliers (PMTs).

The main interaction expected in the liquid scintillator, at the typical energies of neutrino from GSC (some tens of MeV), is the inverse beta decay (IBD): $\bar{\nu}_e p \rightarrow e^+ n$. It gives two detectable signals: the prompt one due to the $e^+$ (visible energy $E_{\text{vis}} \approx E_{\bar{\nu}_e} - Q + m_e = E_{\bar{\nu}_e} - 0.789$ MeV ), followed...
by the delayed one from the neutron capture on proton, $E_\nu = 2.23$ MeV, with a mean capture time, in one LVD counter, of $\tau = 185 \pm 5 \mu s$. The trigger condition for the experiment is the coincidence above threshold $H$ of all three PMTs of any counter. If a trigger occurs, the threshold is lowered to a level $L$ for $\sim 1$ ms in all the counters of the same module of that which gave the trigger, in order to look for the delayed $\gamma$ pulse from neutron capture on proton. The energy release in one counter to get a 50% probability to trigger occurs, the threshold is lowered to a level $L$ for $\sim 1$ ms in all the counters of the same module of that which gave the trigger, in order to look for the delayed $\gamma$ pulse from neutron capture on proton. The energy release in one counter to get a 50% probability to generate a $H$ trigger is $E_H = 4$ MeV, if the average over all the counters is considered. For the $L$ triggers it is $E_L < 0.5$ MeV.

The duty cycle of LVD has been on average $\geq 99\%$ since 2001. It is shown in figure 1 (in black) together with the active mass (in red). Beyond the active scintillator ($M = 1$ kt) the iron supporting structure of the detector ($M = 0.85$ kt) can also act as a passive target for neutrino and products of the interactions can be detected.

Besides interactions with free protons LVD is also sensitive to charged current interactions with carbon and iron nuclei through:

- $\nu_\tau^{12}$C, $^{12}$N $e^-$, (physical threshold $E_{\nu_\tau} > 17.3$ MeV) observed through two signals: the prompt one due to the $e^-$ ($E_d \simeq E_{\nu_\tau} - 17.3$MeV) followed by the signal from the $\beta^+$ decay of $^{12}$N (mean life $\tau = 15.9$ ms);

- $\bar{\nu}_\tau^{12}$C, $^{12}$B $e^+$, (physical threshold $E_{\bar{\nu}_\tau} > 14.4$ MeV) observed through two signals: the prompt one due to the $e^+$ ($E_d \simeq E_{\bar{\nu}_\tau} - 14.4$ MeV + $2m_e c^2$) followed by the signal from the $\beta^-$ decay of $^{12}$B (mean life $\tau = 29.4$ ms);

- $\nu_e^{56}$Fe, $^{56}$Co $e^-$, where the mass difference between the nuclei is $\Delta m \equiv m_{^56}$Co $- m_{^56}$Fe = 4.055 MeV, and the first Co allowed state at 3.589 MeV; the efficiency for electron and gammas, also produced in the interaction, to reach the scintillator with energy higher than $E_H$ has been simulated [8]; on average, the detectable electron energy is $E_d \simeq 0.45 \times E_{\nu_e}$.

- $\nu_e^{56}$Fe, $^{56}$Mn $e^+$.

And neutral current interactions through:

- $\bar{\nu}_\ell^{12}$C, $\nu_\ell^{12}$C$^*$ ($\ell = e, \mu, \tau$), (physical threshold $E_{\ell} > 15.1$ MeV), whose signature is the monochromatic photon from carbon de-excitation ($E_\gamma = 15.1$ MeV);

- $\nu_e^{56}$Fe, $\nu_\ell^{56}$Fe$^*$ ($\ell = e, \mu, \tau$), (physical threshold $E_{\ell} > 7.6$ MeV);

- $\nu e^-$, $\bar{\nu} e^-$, which yields a single signal due to the recoil electron.

To evaluate the number of detected events in LVD for a neutrino burst from GSC we consider a parameterized model, whose parameters have been determined by a maximum likelihood procedure on the data from SN 1987A [9]. From this model the average $\nu_e$ energy is $E_{\nu_e} = 14$ MeV, the total radiated energy $E_b = 2.4 \times 10^{58}$ erg, assuming energy equipartition and normal mass hierarchy for neutrino oscillations. If we set the distance of the collapsing star to $D = 10$ kpc, we get that a total of 300 triggers are expected in LVD with a 1 kt active mass, 85% of which are due to IBD. The energy spectrum would have a mean value of 18 MeV.

2 The search for supernova neutrino bursts

The analysis presented here considers the period from May 1st, 2009 to March 27th, 2011, for a total live time of 696.32 days. All the triggers with energy in the interval 7-100 MeV are selected. A cut on crossing muons is applied excluding the triggers in different counters in coincidence within 250 ns. Some quality cuts are included to avoid electronic noise that can affect data and to exclude counters with unstable counting rate. They are described in detail in [10]. The total rate after these selections is 0.2 s$^{-1}$.

The neutrino burst candidates selection acts on a pure statistical basis. The algorithm is based on the search for clusters of triggers within a fixed time window, $\Delta t = 20$ s. The candidate is simply characterized by its multiplicity $m$, i.e., the number of pulses detected in $\Delta t$. All the other characteristics of the cluster, detailed time structure, energy spectra, $\nu$ flavor content and topological distribution of signals inside the detector are left to a subsequent independent analysis. In detail, the time sequence of total duration $T$, is scanned through a sliding window of duration $\Delta t = 20$ s, that is, it is divided into $N = 2 \times \frac{T}{\Delta t} - 1$ intervals, each one starting in the middle of the previous one (in this way the maximum unbiased time window is 10 s). The frequency of clusters of duration 20 s and multiplicity $\geq m$, i.e., the imitation threshold due to background, is:

$$F_{im}(m, f_{bk}) = N \cdot \sum_{k \geq m} P(k; \frac{20 \cdot f_{bk}}{s^{-1}}) \text{ ev \cdot day}^{-1}$$

where: $f_{bk}$ is the background counting rate of the detector for $E \geq E_{cut}$; $P(k; f_{bk} \Delta t)$ is the Poisson probability to have clusters of multiplicity $k$ if $(f_{bk} \Delta t)$ is the average background multiplicity, and $N = 8640$ is the number of trials per day. This search for neutrino burst candidates is performed simultaneously for trigger energies $E > 7$ MeV ($f_{bk} = 0.2$ Hz) and $E > 10$ MeV ($f_{bk} = 0.03$ Hz), being $N' = 2N$ the effective number of trials.

We can choose different values of $F_{im}$, to which a different minimum multiplicity of the cluster corresponds. We check, for various $F_{im}$, the delay between a selected cluster and the following one. Then we
Figure 1: Duty cycle (in black) and active mass (in red) as a function of time, updated to March 27th 2011. The 300 t mass level is marked by the blue horizontal line.

We couldn’t select any over the whole period under study, so no evidence for a neutrino burst from GSC is found.

Figure 2: Distribution of the observed time delay between alerts selected at different imitation threshold ($F_{im}$) from 1 hour$^{-1}$ up to 1 month$^{-1}$, compared with the expected distribution (dashed lines) at the corresponding threshold. At the level of $F_{im} < 1$ year$^{-1}$ we found two clusters, and both of them had a $F_{im} \sim 1$ year$^{-1}$.

The good agreement among predicted distributions and results from data means that the background is understood and under control. Given this condition we may define as neutrino burst candidates those clusters which would be produced by background fluctuations less than 0.01 year$^{-1}$.

After this pure statistical selection a complete study of selected clusters is planned, to test their consistency with the expectations for real GSC neutrino bursts. In particular this second level analysis focuses on:

1. **The topology of the cluster**, i.e., how the events of the cluster are distributed inside the detector. LVD can identify the counter where an event occurred. We expect that a neutrino burst would distribute uniformly in the detector, while events from the background favour external counters over the internal, more shielded, ones.

2. **The number and temporal distribution of $n$-captures signal.** As a real GSC neutrino burst would mainly interact through IBD, we do expect that $n$-capture signals after the triggers are actually present. Moreover, their temporal distribution should be exponential decreasing with a mean time $\tau \sim 185 \mu s$.

3. **The energy spectrum.** Events from a GSC neutrino burst peak at around 20 MeV, while the events from the background reach their maximum just at the energy threshold (7 MeV or 10 MeV).

We applied the statistical selection of clusters with $F_{im} < 0.01$ year$^{-1}$. We couldn’t select any over the whole period under study, so no evidence for a neutrino burst from GSC is found.
3 Discussion and conclusions

We may consider the null results for the search of GSC neutrino bursts over the whole period of data taking of the experiment, from June 6th, 1992 to March 27th, 2011, for a total of 6314 days live-time. It results that the 90% c.l. upper limit to the rate of gravitational stellar collapses in our Galaxy is 0.13 events/year. The summary of the features of all LVD data runs is reported in Table 1.

The selection method, as it follows from equation 1, defines a candidate as any cluster of \( m \geq m_{\text{min}} \) signals within a window of \( \Delta t = 20 \) s. For a known background rate, \( m_{\text{min}} - f_{\text{bk}} \Delta t \) is the minimum number of neutrino interactions required to produce a supernova alarm at a selected \( F_{\text{im}} \) threshold. We consider the number of signals expected from a SN1987A-like event occurring at different distances, for \( E_{\text{cut}} = 7 \) and \( E_{\text{cut}} = 10 \) MeV and for two values of the detector active mass, \( M_{\text{act}} = 300 \) t and \( M_{\text{act}} = 1000 \) t. Taking into account Poisson fluctuations in the cluster multiplicity, we derive the detection probability as a function of the distance shown in figure 3 (lower scale) for LVD working stand-alone. The detection probability as a function of neutrino luminosity in terms of percentage of SN1987A at the distance of 10 kpc is shown in the upper scale (see details in [10]). It results that LVD is able to monitor the Galaxy \( (D \leq 20 \text{kpc}) \) at full efficiency for both energy thresholds (7 MeV and 10 MeV) when the active mass is greater than 300 t.

In conclusion, LVD has been monitoring the Galaxy since 1992 in the search for neutrino bursts from gravitational stellar collapses with an high duty cycle (greater than 99% in the last ten years). No GSC neutrino burst candidate has been found over 6314 days of live-time, the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy \( (D \leq 20 \text{kpc}) \) is 0.13 events / year.

Table 1: LVD data runs

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Figure 3: Detection probability versus distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for \( E_{\text{cut}} = 7-10 \) MeV (light green and dark blue lines, respectively) and \( M = 300 \) t (dotted) and 1000 t (continuous) for LVD stand alone.

References