Subnuclear Physics: Past, Present and Future
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Status and Results of the LVD Experiment

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1 Introduction and generalities

The sudden appearance of a new bright star in the otherwise immutable sky was observed since ancient times. The study of historical records worldwide allows to identify 6 such events as supernova explosions occurred in our Galaxy, the first one recorded by Chinese astronomers in 185 AD, the last one observed in Europe in 1604 and studied in detail by Kepler.

In the XXth century nuclear and particle physics made possible the early recognition of the role of nuclear fusion reactions and neutrinos in the stellar evolution and in particular in the gravitational core collapse of massive stars where neutrinos are thought to be the instrumental in causing the final supernova explosion.

Stars are maintained in a quasi equilibrium state by the opposite effects of the gravity's pull and of the energy released by the nuclear reaction that fuse the hydrogen in the star core into helium. When most of the hydrogen in the core has been burned the fusion reaction stops, the core contracts and its temperature increases. If the star is massive enough the core temperature become so high that the fusion of helium into carbon starts and the quasi equilibrium state in reconstituted. Massive stars, $M > (6 \div 10)\ M_{SUN}$, can repeat this process in a succession of increasingly shorter and more violent steps, producing heavier and heavier elements until they reach a structure where an iron core is surrounded by shells of lighter elements. Since ^{56}Fe is the most stable nucleus no further exothermic nuclear fusion reactions are possible. The iron core contracts and if its mass overcomes the Chandrasekhar limit it collapses until nuclear matter density is reached. The collapse gets halted and a rebound shock wave is generated that propagates outward through the core and eventually causes the supernova explosion leaving a remnant neutron star. From the start of the collapse to the cooling of the resulting neutron star the most of the gravitational binding energy (a few 10^{53} erg) is carried away by neutrinos and antineutrinos of all species in a time interval estimated to be a few tens of seconds. That's why neutrinos are thought to have a fundamental role in causing the supernova explosion.

At 7:36 (UT) of 23 February 1987 a neutrino signal from a stellar core collapse occurred 170.000 years ago in the Large Magellanic Cloud (an irregular small galaxy not too far from the Milky Way) was detected by several experiments: Kamiokande II (20 events), IMB (8 events), Baksan (6 events) and perhaps LSD (Costantini et al. 2004).

As the cross section of the reaction ($\bar{\nu}_e p, n e^+$) is by far the largest of those detectable by the experiments one can assume that basically all the observed events were due to $\bar{\nu}_e$. Neglecting neutrino oscillation effects the SN1987A observation suggests a reasonable agreement with theoretical expectations in terms of the duration of emission, the total amount of energy released in $\bar{\nu}_e$ and their mean energy.

However, due to a number of puzzling features present in the data, no firm conclusions can be drawn from this first landmark observation of extragalactic neutrinos, the only one detected so far.

On the other hand also the theoretical models need to be improved since they have problems in reproducing the supernova explosion (the shock wave dissipates most of its energy in the photodisintegration of the iron core) and the production of elements heavier than iron.

The experimental data needed to improve the theoretical understanding have to come from the measurements performed in the occasion of the next galactic gravitational stellar collapse. Considering the expected rate of these events (2 ± 1 /100 years) and the experimental difficulties in measuring the energy, flux, flavor of the neutrinos in the various phases of the collapse, this is not an easy task and certainly different experiments using different neutrino detection techniques are required. Table I shows the experiments capable to detect a galactic supernova presently in operation; the neutrino detection techniques are also shown together with mass, expected events number and status.

Detector	Type	Location	Mass (kton)	Events @ 8 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	600	10^6	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
Icarus	Liquid argon	Italy	0.6	60	Running

Table I: Presently running experiment with supernova neutrino detection capabilities.

2 The LVD experiment

The Large Volume Detector (LVD), installed in the INFN Gran Sasso National Laboratory (Assergi, Italy) at a depth of 3600 m.w.e., is a 1 kt liquid scintillator detector whose main purpose is to detect and study neutrino bursts from galactic gravitational stellar core collapses. The experiment started taking data in June 1992 (Aglietta et al. 1992) and has continued without interruptions up to this date.

The LVD apparatus, schematically shown in Fig. 2.1, consists of 840 liquid scintillation counters, 1.5 m^3 each. Clusters of 8 counters are hosted into an iron support module which is in turn inserted in the overall LVD mechanical structure (not shown in figure). The 105 modules are distributed in the structure to form 3 separate identical arrays (named “towers”) each comprising 35 modules arranged in a matrix of 7 rows and 5 columns. Each tower has independent power supply, trigger and data acquisition systems.

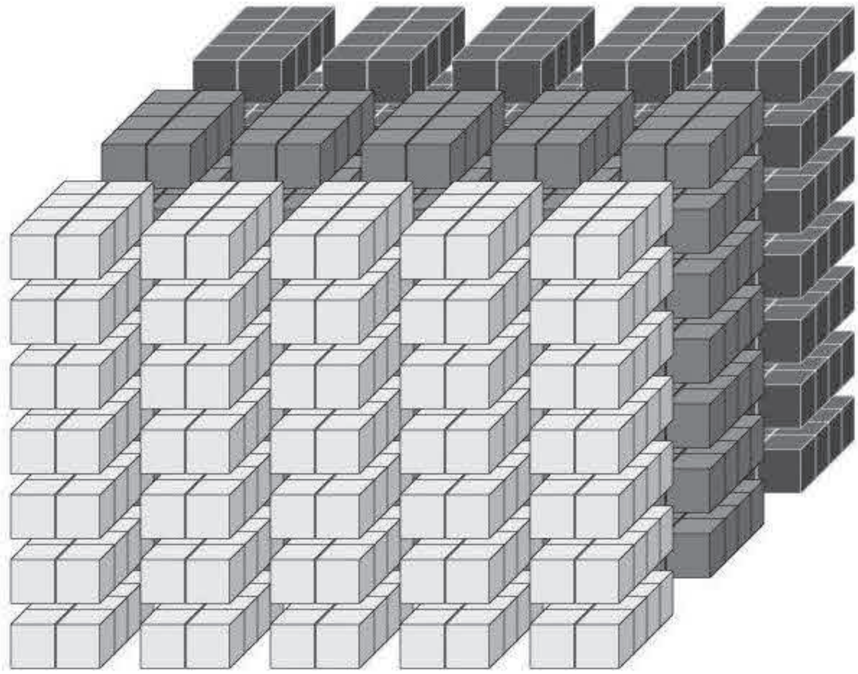

Fig. 2.1 Schematic view of the LVD apparatus.

Each counter is viewed from the top by three Φ=15 cm photomultiplier tubes (PMTs) FEU49 or FEU125. The liquid scintillator is C_nH_{2n} with $<n>$ =9.6 doped with 1g/l of PPO (scintillation activator) and 0.03 g/l of POPOP (wavelengthshifter). The liquid scintillator density is ρ = 0.8 g/cm^3.

In addition to the liquid scintillator also the iron of the counters hosting modules (0.9 kt) contributes to the active mass of LVD since neutrino interactions in the iron can be detected in the scintillation counters.

The signals from the three PMTs of a counter are summed and the sum charge is digitized by a non linear 12 bit ADC (conversion time 1μs). The time is measured with a relative granularity of 12.5 ns and an absolute one of 100 ns.

The modularity of the apparatus allows for calibration, maintenance and repair interventions without major negative interference with data taking and detector sensitivity. Fig. 2.2 shows the duty cycle (black) and the trigger active mass (red) of LVD from June 1992 to March 2011. From 2001 the experiment has been in very stable conditions with duty cycle $\geq$ 99% and slightly increasing active mass. The active trigger mass limit (300 t) at which LVD can monitor the whole Galaxy for gravitational core collapses, is also shown (blue).

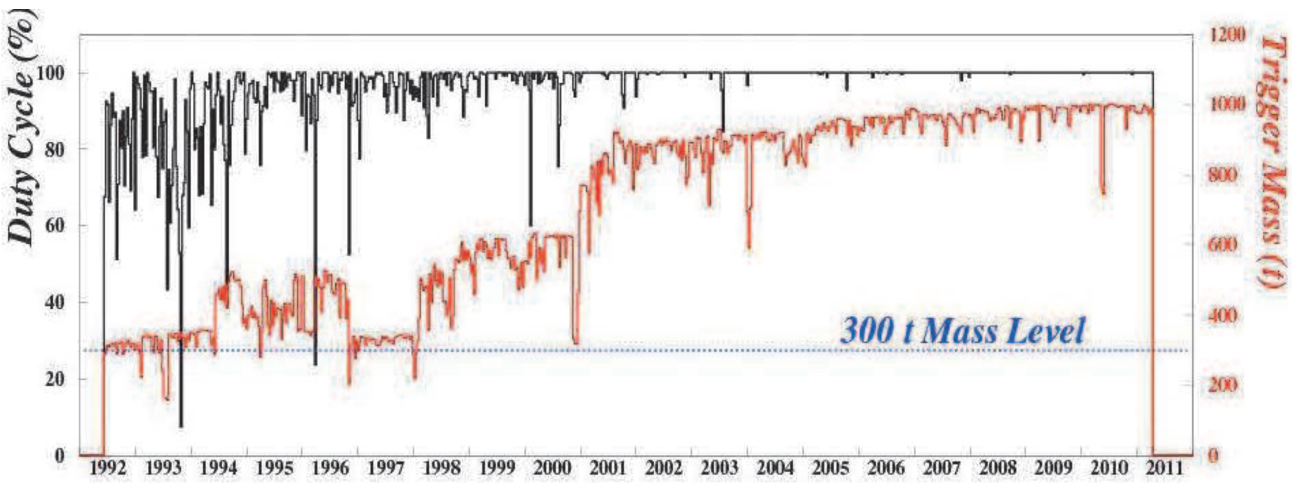

Fig. 2.2 – LVD Duty Cycle and Active Mass in the period June 1992 – June 2011.

The main LVD reaction is the inverse beta decay ($\overline{\nu}_e p, ne^+$) which gives two signals: a prompt one due to the e^+ followed by the signal from the neutron capture reaction ($np, d\gamma$) with mean capture time of about 185 μs and $E_\gamma = 2.2\ MeV$.

Charged and neutral current reactions due to the three neutrino species provide astrophysical informations on the nature of the collapse and are sensitive to intrinsic neutrino properties. They can give an important contribution to define some of the neutrino oscillation properties (Agafonova et al. 2007).

The trigger logic is optimized for the detection of both products of the inverse beta decay reaction and is based on the three-fold coincidence of a counter PMTs. Each PMT is discriminated at two different levels, $E_{High} \cong$ 4 MeV and $E_{Low} \cong$ 0.5 MeV, resulting in two possible levels of coincidence between the three PMTs: High Energy Threshold (HET) and Low Energy Threshold (LET).

A HET coincidence signal in any counter represents the trigger condition for the 8 counters in the module. Once the trigger counter has been identified the charge of the 3 PMTs summed signals and the time of their coincidence are stored in a memory buffer. For all LET coincidences occurring in anyone of the 8 counters in the same module of the trigger counter within 1 ms from the trigger, the charge of the three PMTs summed signals and the coincidence time are also recorded.

Starting 1 ms after the occurrence of a trigger, the read out of the memory buffers, one per module, containing the charge and time information of both HET and LET signals, is performed independently on the three towers without introducing any dead time.

3 The LVD search for gravitational core collapses

To ensure the efficient monitoring of gravitational core collapses even in regions obscured to optical observation the LVD detector capability to identify a neutrino burst in the absence of an external trigger has been investigated. If optical observation is possible the prompt identification of the neutrino burst could then alert the astronomical community and allows the observation of a supernova explosion as near as possible to the onset.

The basis of the on-line search for neutrino bursts with LVD is the identification of clusters of HET triggers in a 10 s wide time window (Agafonova et al. 2008). As a first step the on-line monitor applies the following cuts to the data. The energy E of the scintillation counter pulses must be in the range $E_{cut} \leq E \leq 100$ MeV, with two values for E_{cut} : 7 MeV and 10 MeV.

Events with signals in time coincidence within 200 ns in 2 or more counters are identified as muons and rejected.

Not properly working counters identified by their response to atmospheric or CNGS muons, are rejected. These counters are usually less the 5% and represent a steady loss of active mass requiring a maintenance intervention typically on the associated PMTs, ADC or TDC.

Counters with background rate $R \geq 3{\cdot}10^{-3}$ s^{-1} for $E \geq 7$ MeV during the last two hours of operation are rejected as noisy. These counters are usually less than 2%. The problem is cured by maintenance intervention on the electronics or a new energy calibration.

The effect of the cuts on counters is to adjust dynamically the LVD active mass which is, as shown in Fig. 2.2, quite stable starting from 2001 when the detector reached its final configuration.

The average background counting rate of the whole LVD array is then typically $f_{bk} = 0.2$ Hz with $E_{cut} = 7$ MeV and $f_{bk} = 0.03$ Hz with $E_{cut} = 10$ MeV.

After this selection procedure the time distribution of the HET triggers is well described by the Poisson statistics as can be seen in Fig. 3.1, where the time difference between successive signals is shown and in Fig. 3.2 which shows the fluctuations f_5 of the 5 m counting rate, s_5, with respect to the average value measured in a time interval of 40 min, in units of the expected error σ_{exp} calculated assuming pure Poisson fluctuations:

$$f_5 = \frac{s_5 - \bar{s}_5}{\sigma_{\rm exp}}$$

The experimental distribution, obtained during 100 days of operation is fitted with a Gaussian with mean equal zero and $\sigma = 1.01$ showing that the residual non-Poisson contribution to the fluctuations,

$$\sigma_{res} = \sqrt{\sigma^2 - 1}$$

is less than 15%.

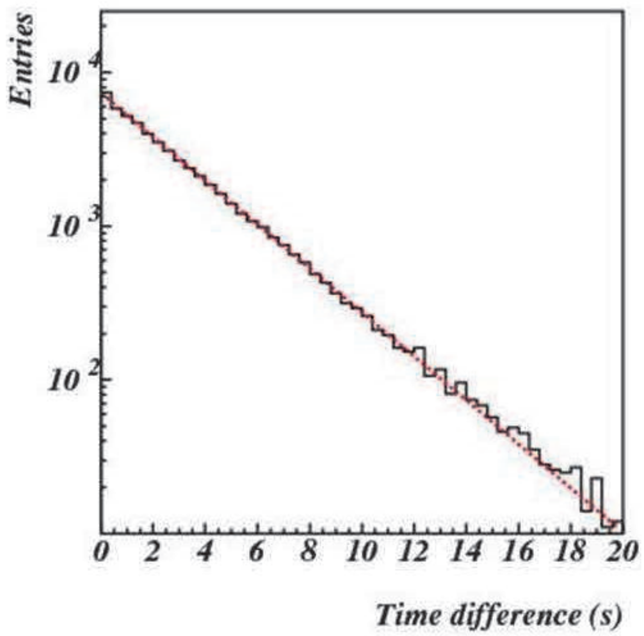

Fig. 3.1 Distribution of the difference of the arrival time between successive signals compared with Poisson expectations (red dotted line).

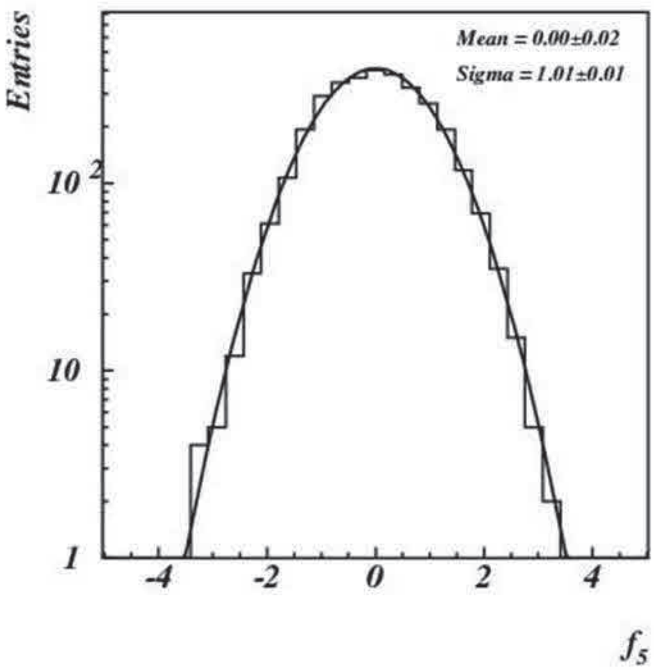

Fig. 3.2 Distribution of the fluctuations of the 5 minutes counting rate. The superimposed curve is the free parameter Gaussian fit.

As the time distribution of the background is purely statistical the candidate neutrino burst is simply characterized by the multiplicity of HET triggers detected in a time window, Δt. All other characteristics as detailed time structure, energy spectra, topological distribution of signals inside the detector can be left to a subsequent off-line analysis.

Each data period, T, is scanned through a "sliding window" with duration Δt = 20 s and is divided into $N = 2 \cdot T/\Delta t - 1$ intervals, each one starting in the middle of the previous one so that the 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:

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

Where f_{bk} is the background counting rate (in Hz) of the detector for $E \geq E_{cut}$, $P(k; 20 \cdot f_{bk})$ is the Poisson probability to have clusters of multiplicity k if ($20 \cdot f_{bk}$) is the average background multiplicity and N is the number of trials per day.

As mentioned above the on-line search for neutrino burst candidates is performed for two values of the energy cut: $E_{cut} \geq 7$ MeV (with a corresponding f_{bk} = 0.2 Hz) and : $E_{cut} \geq 7$ MeV (with a corresponding f_{bk} = 0.03 Hz).

When LVD operates in standalone the imitation frequency threshold to identify on-line a cluster as a neutrino burst candidate is set to 1 event in 100 years. Since 2005 LVD participates to the Supernova Early Warning System (SNEWS) an international collaboration including several experiments sensitive to galactic stellar gravitational core collapses (LVD, Borexino, SuperKamiokande, Ice-Cube) aiming to provide the worldwide network of observatories with a prompt and reliable alert generated by the coincidence of at least two of the participating experiments. In the framework of the SNEWS project the LVD imitation frequency threshold may then be relaxed to 1 event per month.

Less sensitive thresholds on F_{im} are used for monitoring purposes and as a test of the stability of the overall procedure. Fig 3.3 shows the rate of clusters with F_{im} = 1/day as measured in the 5 years period from 2006 to 2010.

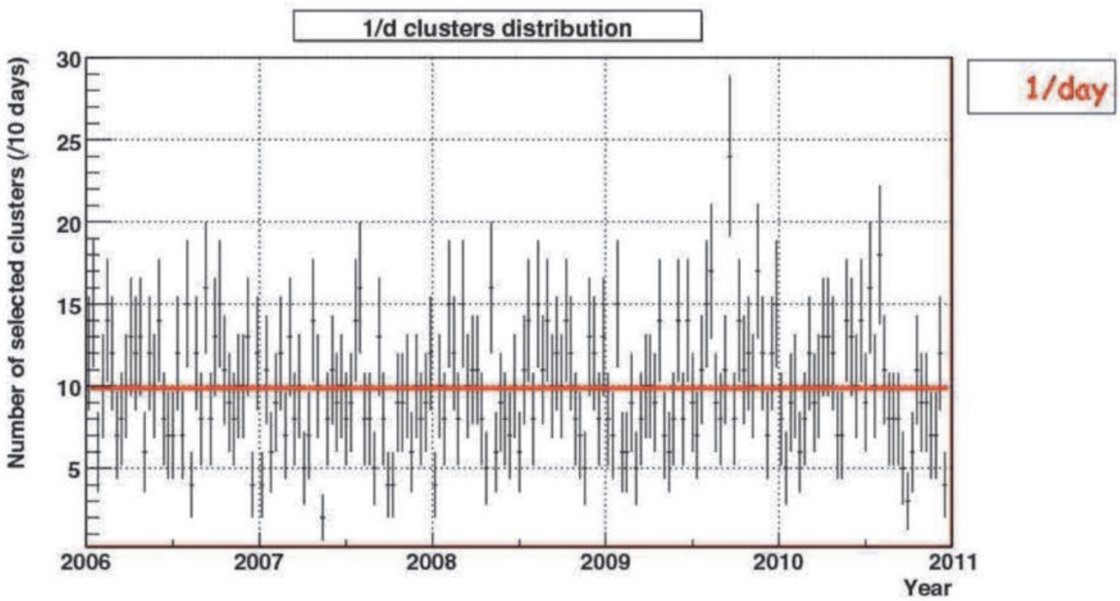

Fig. 3.3 The rate of clusters with 1/day imitation frequency from 2006 to 2010.

To determine the LVD on-line trigger efficiency we proceed as follows. For known values of f_{bk}, Δt and of the selected imitation frequency threshold, F_{im}^{thr}, we derive the minimum multiplicity value m_{min} of a cluster to be identified as a neutrino burst. The difference $(m_{min} - f_{bk} \cdot \Delta t)$ represents therefore the minimum number of neutrino interactions to produce a supernova alarm at the selected imitation frequency threshold. Assuming a model for the neutrino emission and propagation and taking into account the apparatus detection efficiency, we calculate the number of observed interactions and the detector trigger efficiency as a function of the source distance or as emitted neutrino flux can be derived.

As the astrophysical parameters of the Supernova mechanism are still not well defined we have adopted the following conservative values (Pagliaroli et al. 2009): average $\overline{\nu}_e$ energy $\langle E_{\overline{\nu}_e}\rangle = 14\,MeV$; total gravitational binding energy $E_b = 2.4{\cdot}10^{53}\,erg$ and average non-electron neutrino energy 20% higher than $\overline{\nu}_e$.

Concerning neutrino oscillations we conservatively considered normal mass hierarchy and non-adiabaticity. Taking into account Poisson fluctuations in the cluster multiplicity, we derived the trigger efficiency shown in Fig. 3.4 as a function of the distance for LVD working in standalone and in Fig. 3.5 for LVD working in coincidence with other detectors.

We can conclude that, without introducing any further check on the time structure, energy spectra and neutrino flavor content of the signals in the cluster (which are postponed to the off-line analysis), LVD with an energy cut of $E_{cut} \geq 7$ MeV and $F_{im}^{thr} = \frac{1}{100} y^{-1}$ is able to identify on-line neutrino bursts from gravitational stellar collapses occurring in the whole Galaxy (D ≤ 20 kpc) with efficiency > 90%. Such a sensitivity is preserved in the same conditions even if the detector is running with only one third of its total mass. Due to the better signal to noise ratio introducing a cut on the visible energy at 10 MeV, the 90% LVD on-line trigger efficiency extends up to 50 kpc (corresponding to the Large Magellanic Cloud).

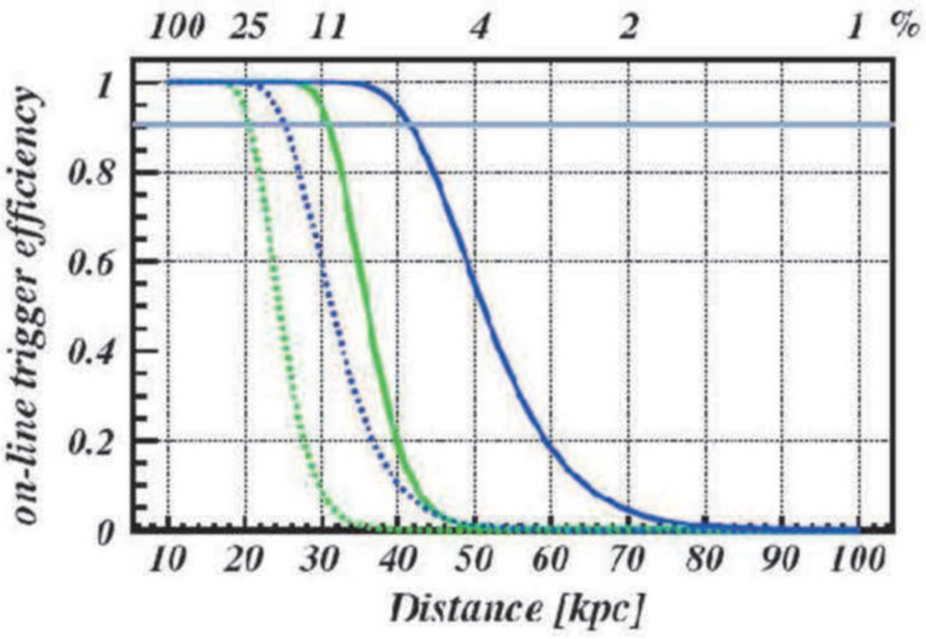

Fig. 3.4 Trigger efficiency versus distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for E_{cut}= 7 – 10 MeV (light green and dark blue lines, respectively) M=300 t (dotted) and 1000 (continuous) for LVD standalone (F_{im} = 0.01/year).

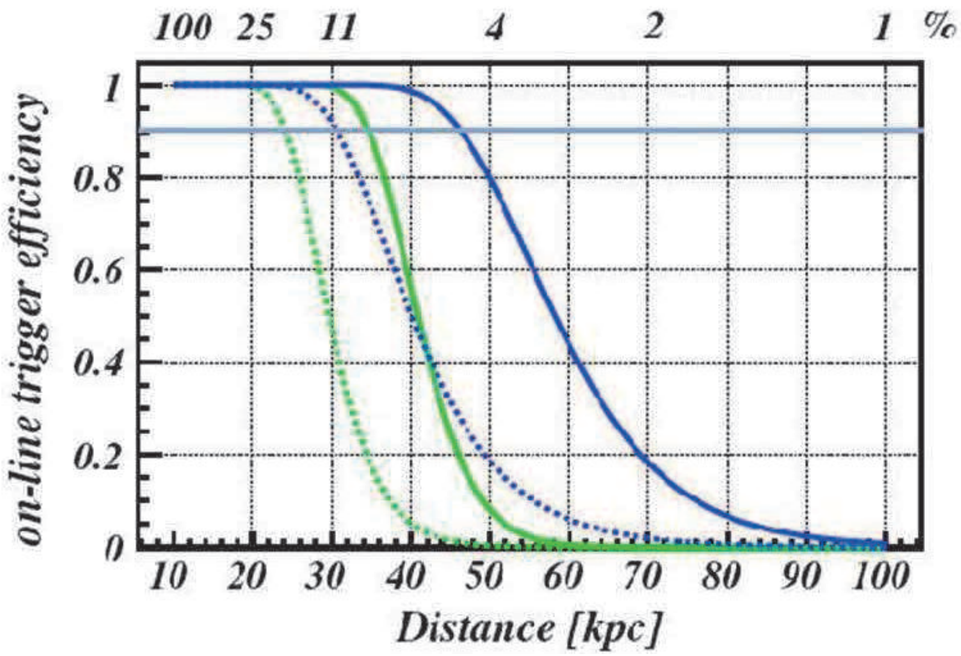

Fig. 3.5 Trigger efficiency versus distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for E_{cut}= 7 – 10 MeV (light green and dark blue lines, respectively) M=300 t (dotted) and 1000 (continuous) for LVDin SNEWS (F_{im} = 1/month).

For what concerns the off-line analysis in addition to the selections already made at the on-line level applied with more refined calibrations, we search for clusters in time windows starting at each HET trigger and with a variable width (from 10 up to 100 s) and determine their imitation frequency F_{im}.

For all clusters with $F_{im} \leq$ 1/day a complete analysis is performed to test their consistency with a neutrino burst in terms of the topological distribution inside the LVD array, energy spectrum and time distribution of the HET signals in the cluster and time distribution of delayed LET pulses, signature of $\overline{\nu}_e$ interactions.

No candidates have been found since 1992, see detail in table II. The resulting LVD 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy (D ≤ 20 kpc) is therefore 0.13 y^{-1}.

RUN	SINCE	TO	LIVETIME	DUTYCYCLE	MASS
1	06/06/1992	05/31/1993	285 days	60%	310 t
2	08/04/1993	03/11/1995	397 days	74%	390 t
3	03/11/1995	04/30/1997	627 days	90%	400 t
4	04/30/1997	03/15/1999	685 days	94%	415 t
5	03/16/1999	12/11/2000	592 days	95%	580 t
6	12/12/2000	03/24/2003	821 days	98%	842 t
7	03/25/2003	02/04/2005	666 days	>99%	881 t
8	02/04/2005	05/31/2007	846 days	>99%	936 t
9	05/31/2007	04/30/2009	669 days	>99%	967 t
10	05/01/2009	03/27/2011	696 days	>99%	981 t
Σ	06/06/1992	03/27/2011	6314 days		

Table II: LiveTime, Duty Cycle and Active Mass for the 10 LVD data taking runs from June 1992 to March 2011.

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