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Search for events in the LVD detector coinciding with gravitational signals from the collapse of close binary systems

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Abstract. The results of the search for events detected by the Large Volume Detector coinciding with the gravitational signals from the GW150914, GW151226, GW170104, GW170608, GW170814 and GW170817 are presented.

1. Introduction

Close binary systems, such as neutron stars or black holes, constantly emit gravitational waves. Their orbits are gradually reduced, this ultimately leads to the merging of stars and a powerful gravitational wave at this moment. GW150914, GW151226, GW170104, GW170608, GW170814 are gravitational-wave bursts detected by the LIGO and VIRGO collaborations. They are caused by the merging of black holes. The first event GW150914 was announced on February 11, 2016. Observation of gravitational waves by experiments of LIGO and VIRGO [1, 2, 3] initiated an intensive search for events in the signals of neutrino detectors.

The Cherenkov neutrino telescopes ANTARES, IceCube [4] and the Observatory Pierre Auger [5] searched for high-energy neutrinos with energies above 100 GeV and 100 PeV, respectively. The search for antineutrino events with energies from 1.8 to 111 MeV by the inverse beta decay reaction (IBD) was carried out in the KamLAND experiment [6]. The Super-Kamiokande collaboration reported the results of a search for signals induced by neutrinos in the energy range from 3.5 MeV to 100 PeV [7]. The BOREXINO collaboration [8] analyzed detected events in the energy range from 0.25 to 15 MeV. The search for neutrino and antineutrino interactions was carried out in the time interval of $\pm$ 500 seconds around the time of gravitational waves detection, but no candidates for neutrino events were found.

Electromagnetic detectors [9, 10, 11, 12] also did not detect anomalous events in different electromagnetic radiation ranges with the exception of a slight excess above 50 keV and 0.4 during the GW150914 signal. The gravitational signal from GW170817, detected on August 17, 2017 at 12: 41: 04.4 UTC by all three laser-interferometric gravitational-wave detectors of the LIGO-Virgo network, is most likely caused by the merging of two neutron stars with masses of $1.17 - 1.60$ $M_{\odot}$. Also, 1.7 seconds after the time of GW170817, a short gamma-ray burst lasting about 2 seconds was recorded, which was designated GRB 170817A. This gamma-ray burst was

Table 1. Gravitational wave signals.

GW (date)	Time, UTC	Distance, Mpc	System type	Chirp mass
GW150914	09:50:45	440^{+160}_{-180}	BH	$28.2^{+1.8}_{-1.7}$
GW151226	03:38:53	440^{+180}_{-190}	BH	$8.9^{+0.3}_{-0.3}$
GW170104	10:11:58	880^{+450}_{-390}	BH	$21.1^{+2.4}_{-2.7}$
GW170608	02:01:16	340^{+140}_{-140}	BH	$7.9^{+0.2}_{-0.2}$
GW170814	10:30:43	540^{+130}_{-210}	BH	$24.1^{+1.4}_{-1.1}$
GW170817	12:41:04	40^{+8}_{-14}	NS	$1.188^{+0.004}_{-0.002}$

observed by the space observatories INTEGRAL [13] and Fermi [14, 15]. At this merging should generate intensive neutrino signal.

The joint analysis of the data of gravitational, neutrino and electromagnetic detectors forms an integrated approach leading to a more complete understanding of astrophysical and cosmological processes.

2. LVD description

The Large Volume Detector (LVD), in the INFN Gran Sasso National Laboratory (Italy), at the depth of 3600 m w. e., is a 1 kt liquid scintillator detector whose major purpose is monitoring the Galaxy to study neutrino bursts from gravitational stellar collapses. LVD has been taking data since June 1992 with increasing mass configurations, its sensitive mass being always greater than 300 t, high enough to cover the whole Galaxy (D $<$ 20 kpc). From 2001 LVD sensitive mass is greater than 1000 t. No candidates have been detected over 26 years of observation: the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy is 0.09 events / year.

LVD consists of an array of 840 scintillator counters, 1.5 m^3 each [16]. The whole array is divided in three identical towers with independent high voltage 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 15 cm photomultiplier tubes (PMTs) FEU49b or FEU125. The modularity of the array allows high duty cycle performance ($\geq$ 99%).

The main neutrino reaction in LVD is $\overline{\nu}_e + p \rightarrow e^+ + n$, which gives two detectable signals: the prompt one due to the e^+ (visible energy $E_{vis} \approx E(\overline{\nu}_e) -$ 1.8 MeV + 2 $m_e c^2$) followed, with a mean delay $\Delta t \approx 185$ μs, by the signal from the $n + p \rightarrow d + \gamma$ capture (E_γ = 2.2 MeV). The trigger logic is optimized for the detection of both products of the inverse beta decay and is based on the three-fold coincidence of the PMTs of a single counter.

Since 2001 an on-line neutrino burst monitor is in operation keeping LVD connected to the SNEWS inter-experiment system.

3. Analysis results

The list of gravitational detector signals and their characteristics is shown in table 1.

We analyzed LVD data while gravity signals were recorded.

The purpose of experimental data selection is the selection of events that could be caused by the neutrino interactions in the LVD detector. At the first stage, events caused by muon interactions in the detector are excluded. Such events are characterized by the response of two or more counters in a time window of less than 250 ns. Also, the data of external counters are analyzed separately from the data of internal counters. External counters are those that form

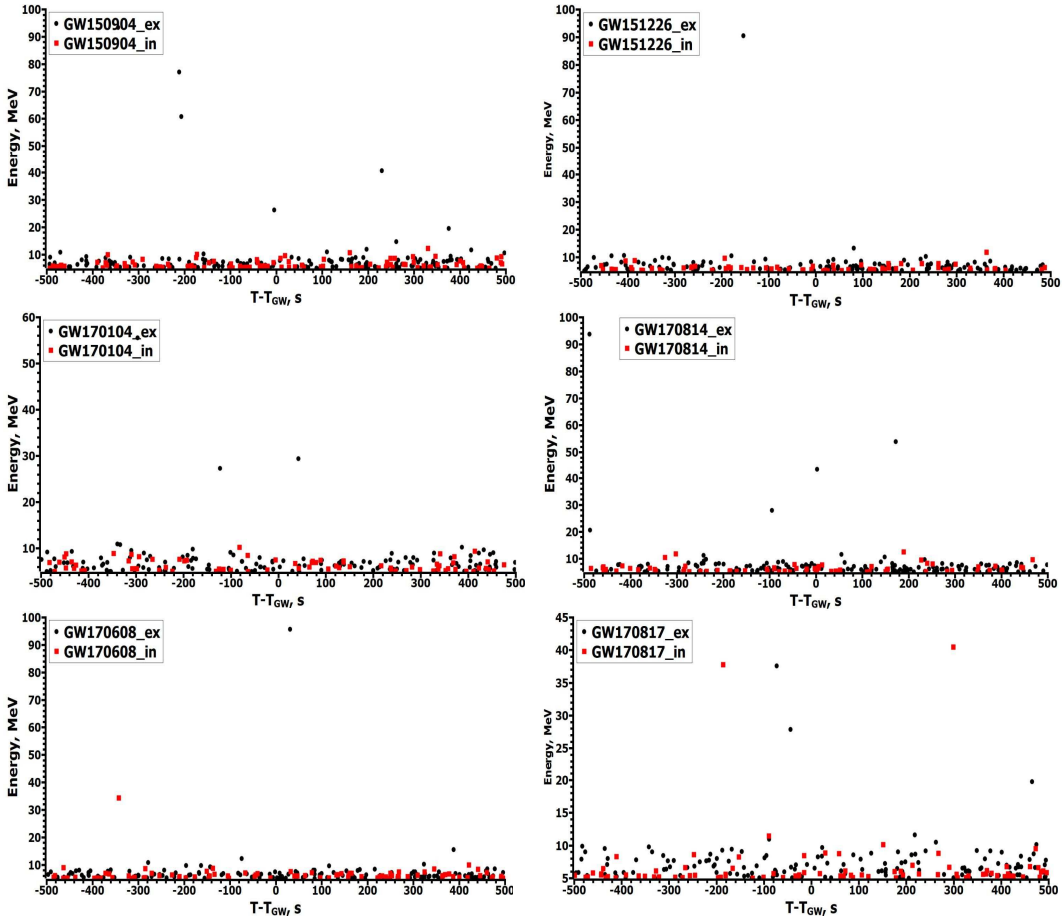

Figure 1. LVD events between 5 MeV and 100 MeV visible energy occurring within ±500 s of the GW signals.

an external rectangular parallelepiped. This definition is caused by the different counting rate of background events in the counters. The counting rate of background events in external counters is several times (about 4) higher than in internal ones. We excluded counters with an extremely high background counting rate from the analysis.

Ultimately, the total number of counters included in the analysis was 583 (291 - internal, 292 - external) of the three LVD towers. The energy range $5 < E_{tr} < 100$ MeV for single triggers was established.

The detection time and visible energy of LVD selected events in ± 500 s temporal windows around GW event are shown in figure 1. The error of each point in energy is about 40%. Time accuracy is 70 nanoseconds. The pulses in the internal counters are marked in red, and the pulses in the external ones in black.

We paid special attention to the GW170817 signal, due to the fact that when neutron stars merge, neutrinos can appear like to a gravitational star collapse. figure 2 shows a histogram of LVD events in 100-second bins ranging from −3000 s to 3000 s around the GW170817 signal. The distributions by the number of triggers for internal and external counters in a 100 second bin over a period of 12 hours before and after GW are show in figure 3.

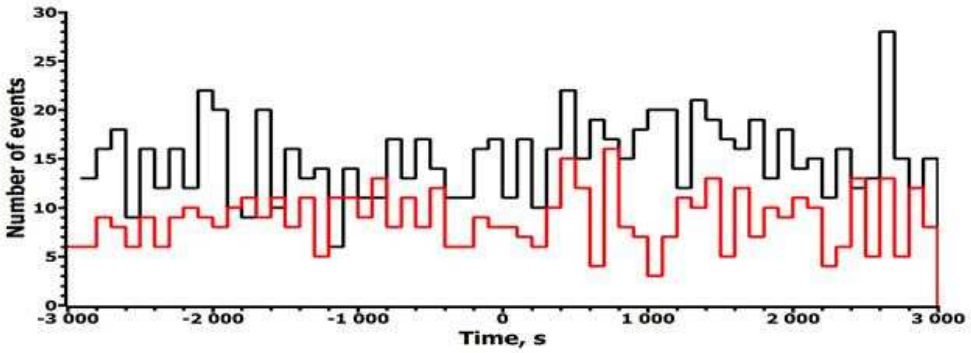

Figure 2. Histogram of LVD events at a bin of 100 s in the range of ± 3000 s around the GW170817 signal. The histogram for the internal counters is in red, and for the external ones - in black.

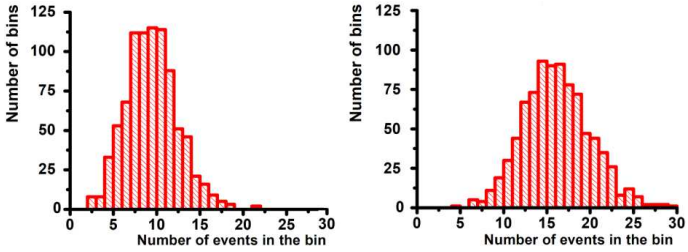

Figure 3. Distribution by the number of triggers for internal (left) and external (right) counters in a 100 second bin.

4. Conclusion

We searched for an excess in the number of events detected by LVD correlated to the GW signals. We found no statistically significant increase in the number of events with an energy greater than 5 MeV in the detector during time windows of ± 3000 s around the GW150914, GW151226, GW170104, GW170608, GW170814 and GW170817 gravitational events.

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