Search for neutrino counterparts of LIGO/Virgo gravitational-wave events

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Abstract. The LIGO/Virgo collaborations have reported the results of their searches for gravitational-waves from the first half of their third observing run. 39 events were combined into the second Gravitational-Wave Transient Catalog (GWTC-2), reaching the total number of 50. In addition to these, two neutron star - black hole merger events were also confirmed. The search for neutrino counterparts of LIGO/Virgo gravitational-wave events was performed on the Baksan Underground Scintillation Telescope. The processing algorithm and the results of the counterpart search are described.

1. Introduction

Nowadays, multimessenger observations are becoming more widespread in the search of astrophysical sources of cosmic radiation. Simultaneous detection of bursts of radiation with several different experimental setups can improve the understanding of processes occurring in astrophysical objects. It can be useful in shortening the time required to detect and confirm an event. The combination of data of two experimental setups can improve the location accuracy, up to the spotting of a specific point source on the skymap. A successful example of such interaction is the simultaneous observation of gravitational wave GW170817 by the Advanced LIGO and Advanced Virgo gravitational-wave detectors and gamma-ray burst GRB170817A by Fermi-GBM [1].

This work presents the results of the search of neutrinos on the Baksan Underground Scintillation Telescope (BUST) in coincidence with confirmed Advanced LIGO and Advanced Virgo gravitational-wave events. Upper limits on the integral fluxes on muon neutrinos and antineutrinos were obtained.

2. Baksan Underground Scintillation Telescope

The Baksan Underground Scintillation Telescope is a multi-purpose detector of the Baksan Neutrino Observatory (Northern Caucasus, Russia) [2]. The effective depth of the BUST location is 850 m of water equivalent. The BUST consists of 3184 scintillation counters. Scintillation counters form 4 horizontal and 4 vertical planes, so that the detector can reconstruct particle trajectories with an angular resolution ≈1.6°. The size of the BUST is $17 \times 17 \times 11$ m^3. Standard scintillation counter is a container

0.7 × 0.7 × 0.3 m^3 filled with liquid scintillator based on white spirit. The scintillation light is collected by the photomultiplier tube FEU-49 with photocathode diameter of 15 cm.

The BUST can distinguish muons from the lower hemisphere using time-of-flight method. The background for the BUST depth is totally excluded for the zenith angles >100°. Since there is no background, it is safe to say that muons from the lower hemisphere are the result of neutrino-matter interaction under the BUST [3]. The direction of the muon generated in such interaction strongly correlates with the initial neutrino direction. The angular uncertainty of muon neutrinos and antineutrinos is ~5°. This uncertainty is determined by the angle of muon generation versus the direction of neutrino arrival and the multiple scattering of a muon as it travels from the point of generation to the experimental setup. The energy threshold for muons crossing the experimental setup is 1 GeV.

3. Search for counterparts

The confirmed events of LIGO/Virgo observatories were sorted into two gravitational-wave transient catalogs – GWTC-1 (11 events) and GWTC-2 (39 events) [4, 5]. The data of these events are in the public domain. The information needed for the counterpart search is the time of the gravitational-wave event and the skymap with distribution of the source localization probability. The 90%-probability regions of gravitational-wave source localization are used in the processing for the comparison of the coordinates.

First, the search for neutrino event on the BUST within time window ±500 s from the moment of each of gravitational wave events is performed [6]. Then, the field of view of the BUST is checked against the region of localization of the gravitational-wave event. As an example, Fig. 1 shows the skymap of the event GW150914. The localization of GW150914 is completely inside the field of view of the BUST.

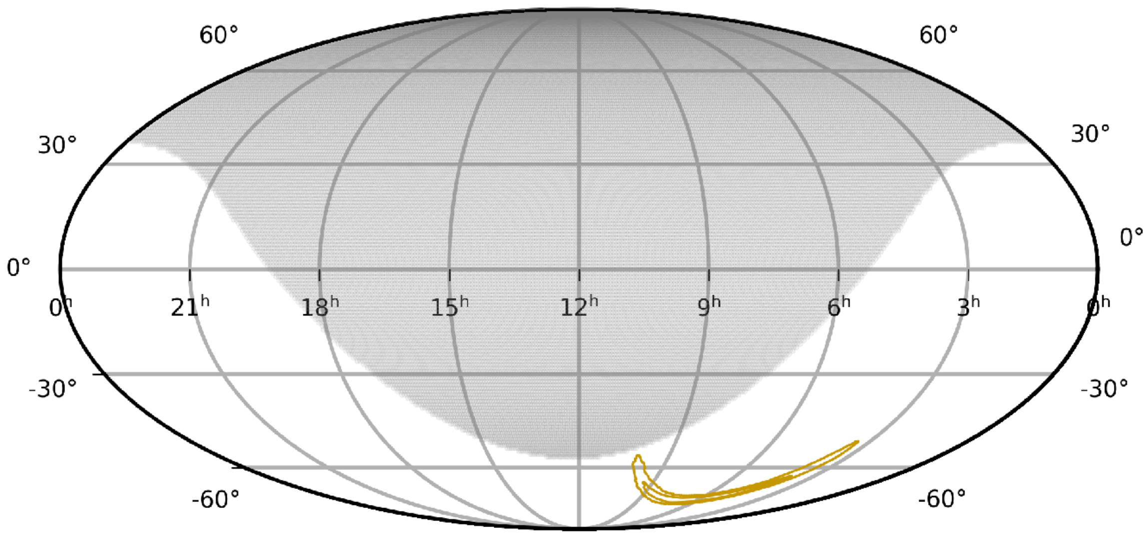

Figure 1. Localization of gravitational-wave event GW150914 and the BUST field of view (light area).

Then, if gravitational-wave localization and the field of view of the BUST do not overlap – the processing is finished. If they do overlap – the direction of neutrino on the BUST is compared with the 90%-probability region of the gravitational-wave localization. If the direction of neutrino lies in the region of the gravitational-wave localization – a counterpart is found.

In case if there are no neutrino events in ±500 s time window or in the 90%-probability region of the gravitational wave localization – the maximum and minimum upper limits on the integral flux are calculated. Upper limits are calculated within the area of overlap of the BUST field of view and the gravitational-wave localization. So far, no neutrino counterparts were found for any of the gravitational wave events.

3.1. Upper limits calculation

As far as there is no neutrino events from the gravitational wave source, the upper limits (at a 90% confidence level) for the integral fluxes of muon neutrinos and antineutrinos are set as a function of their energy for the monoenergetic spectrum:

$$I(E_\nu,\theta,\varphi) = \frac{n_{90}}{S_{eff}(E_\nu,\theta,\varphi)} \qquad (1)$$

where $S_{eff}(E_\nu, \theta, \varphi)$ is the effective area of detection of a muon neutrino (antineutrino) with energy E_ν and direction (θ, φ), $n_{90} = 2.3$ is the limit at a 90% confidence level on the number of events for the Poisson distribution. The effective area is calculated as:

$$S_{eff}(E_\nu,\theta,\varphi) = \sigma_{\nu N}(E_\nu) S_T(\theta,\varphi) L_{eff}(E_\nu) \rho N_A \qquad (2)$$

where $\sigma_{\nu N}$ is the cross section of muon neutrino/antineutrino interaction with a nucleon [7], $S_T(\theta, \varphi)$ is the telescope area in a given direction, $L_{eff}(E_\nu)$ is the effective range of a muon generated by a neutrino with energy E_ν, ρ is the rock density near the telescope, N_A is the Avogadro number. The BUST area $S_T(\theta, \varphi)$ in the area of zenith angles >100° varies from 72 m^2 to 217 m^2. Hence, the upper limits may vary by a factor of three.

Upper limits for integral fluxes are obtained in assumption of power spectrum with exponent −2, for the energy range 1 GeV–10^5 GeV:

$$F = \frac{n_{90}}{\int_{E_{min}}^{E_{max}} dE_\nu S(E_\nu) I(E_\nu)} \qquad (3)$$

where E_{min} = 1 GeV, $E_{max} = 10^5$ GeV, $I(E_\nu) = E_\nu^{-2}$.

Table 1 shows the ranges of the upper limits on fluxes of muon neutrinos and antineutrinos for gravitational waves from catalogs GWTC-1 and GWTC-2. Limits for two confirmed neutron star-black hole merger events are also included [8].

Table 1. Upper limits on the integral fluxes of muon neutrinos and antineutrinos from gravitational-wave events

	Muon neutrinos		Muon antineutrinos	
GW event	F_{min}, cm^{-2}	F_{max}, cm^{-2}	F_{min}, cm^{-2}	F_{max}, cm^{-2}
GW150914	80.580273	166.482705	158.718719	327.92048
GW151012	77.367213	223.726197	152.389964	440.672813
GW151226	78.871889	225.597441	155.353721	444.358596
GW170104	78.641816	219.26984	154.900546	431.89514
GW170608	107.622788	210.622198	211.984279	414.861906
GW170729	85.308212	223.355487	168.031326	439.942627
GW170809	88.863766	157.305979	175.034691	309.845111
GW170814	83.602408	98.215994	164.67141	193.455745
GW170823	80.64053	223.170893	158.837408	439.579031
GW190929_012149	82.845033	231.305193	163.17961	455.601137
GW190915_235702	120.134766	210.622198	236.629085	414.861906
GW190910_112807	86.070453	224.097838	169.53271	441.404832

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GW190909_114149	76.915005	222.068215	151.499253	437.40709
GW190828_065509	114.256471	223.355487	225.050625	439.942627
GW190828_063405	143.382139	224.097838	282.419366	441.404832
GW190803_022701	135.97319	210.622198	267.825979	414.861906
GW190731_140936	77.212177	206.589044	152.084592	406.917814
GW190728_064510	106.538123	215.073302	209.847818	423.629231
GW190727_060333	100.822939	209.071275	198.590637	411.807057
GW190720_000836	101.659226	219.626811	200.23787	432.598264
GW190719_215514	79.230873	221.794172	156.060811	436.867309
GW190708_232457	81.505701	223.726197	160.541532	440.672813
GW190707_093326	77.556179	222.068215	152.762171	437.40709
GW190706_222641	109.768984	231.305193	216.211634	455.601137
GW190701_203306	98.521313	119.126505	194.057131	234.643116
GW190630_185205	102.861254	208.990239	202.605501	411.64744
GW190620_030421	106.202913	223.726197	209.187556	440.672813
GW190602_175927	78.367567	209.233274	154.36036	412.126145
GW190527_092055	77.869654	209.803178	153.379621	413.248683
GW190521_074359	78.413081	216.454185	154.450007	426.349153
GW190521	112.048616	223.355487	220.70182	439.942627
GW190519_153544	85.281051	228.754684	167.977827	450.577408
GW190517_055101	78.906367	211.282195	155.421631	416.161899
GW190514_065416	78.952508	219.26984	155.512516	431.89514
GW190513_205428	98.846183	219.537387	194.697027	432.422126
GW190512_180714	98.503197	214.474725	194.021449	422.450216
GW190503_185404	86.832361	151.347886	171.033438	298.109473
GW190426_152155	85.159913	213.203174	167.739223	419.945645
GW190425	79.091634	225.597441	155.786552	444.358596
GW190424_180648	77.500441	228.754684	152.652384	450.577408
GW190421_213856	78.756685	210.458043	155.126803	414.53857
GW190413_134308	99.35595	217.589171	195.701113	428.584732
GW190413_052954	91.455514	215.67523	180.139649	424.814846
GW190412	97.295323	207.702663	191.642303	409.111307
GW190408_181802	95.149681	219.537387	187.416038	432.422126
GW200105_162426	86.235821	223.726197	169.858436	440.672813
GW200115_042309	81.604226	223.170893	160.735596	439.579031
GW170817		Out of field of view		
GW170818		Out of field of view		
GW190930_133541		Out of field of view		
GW190924_021846		Out of field of view		

GW190814	Out of field of view

4. Conclusion
The BUST was used for the search for neutrino counterparts of confirmed gravitational waves from LIGO/Virgo observatories. No neutrino events were found from any of 52 gravitational wave events. Upper limits on integral fluxes for neutrinos and antineutrinos were calculated. The BUST is capable to search for counterparts in real time when LIGO/Virgo observatories are performing their observing run.

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