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BAIKAL-GVD NEUTRINO TELESCOPE: UNLOCKING THE SECRETS OF THE UNIVERSE'S CATASTROPHIC EVENTS

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Abstract. We briefly review state-of-the-art in neutrino astronomy, a new rapidly evolving branch of multi-messenger astronomy, paying more attention to status of Baikal-GVD neutrino telescope, its commissioning, simulation, data analysis and major results.

1. INTRODUCTION

Neutrino astronomy represents a rapidly evolving field within modern fundamental research. Its primary aim is to identify sources of high-energy astrophysical neutrinos. Possible origins of high-energy neutrinos include active galactic nuclei, blazars, Seyfert galaxies, star-forming galaxies, and tidal disruption events. Weak interactions of neutrinos make them exceptional messengers of astrophysical processes.

Observation of these neutrino require a cubic-kilometer-like detectors to compensate for their tiny flux at ultra-high energies. Presently, several collaborations are engaged in the development of neutrino telescopes, which consist of arrays of optical detectors in a transparent medium. These telescopes detect Cherenkov radiation from charged particles produced in neutrino interactions through charged current (CC) or neutral current (NC) within or near the telescope's volume. Notable among these collaborations are the IceCube neutrino Observatory at the South Pole, as well as two neutrino telescopes situated in the Northern Hemisphere: KM3NeT/ARCA in the Mediterranean Sea and Baikal-GVD in Lake Baikal. While IceCube has already reached its operating volume of one km^3, others are currently undergoing deployment. Baikal-GVD has achieved a volume of approximately 0.5 km^3, and data collection is well underway.

The interaction of galactic cosmic rays (CRs) with interstellar matter creates diffuse galactic neutrino flux arriving on the Earth almost isotropically. Extragalactic CRs from astrophysical sources, such as active galactic nuclei or accreting supermassive black holes, may also be deflected in intergalactic gas, creating a quasi-diffuse astrophysical neutrino flux. Hence, the determination of the diffuse neutrino flux involves the search of astrophysical neutrinos from all parts of the sky. When seeking out point sources of astrophysical neutrinos, the focus shifts to detecting an excess of neutrino events above diffuse background and establishing the statistical connection between the reconstructed direction of neutrino arrival and well-known sources.

A breakthrough result of neutrino telescopes was the pioneering discovery by IceCube (Aartsen et al., 2013) of astrophysical high-energy neutrinos, which reached a 5σ confidence level (C.L.) in 2014 (Aartsen et al., 2014). Subsequently, Baikal-GVD confirmed these findings in 2023 with a 3σ C.L. (Allakhverdyan et al., 2023a).

Several exciting candidates for individual neutrino sources can be highlighted: (i) Blazar TXS 0506 + 056 at 3.5σ C.L. (Aartsen et al., 2018), (ii) Seyfert II galaxy NGC 1068 at 4.2σ C.L. (Abbasi et al., 2022b) and (iii) a correlation of diffuse flux with Milky Way galactic plane at 4.5σ C.L. (Abbasi et al., 2023). However, no source at 5σ C.L. was identified so far.

A staggering 99% of these sources still elude our understanding and the primary challenge to unveil the origin of the neutrino flux remains the major challenge.

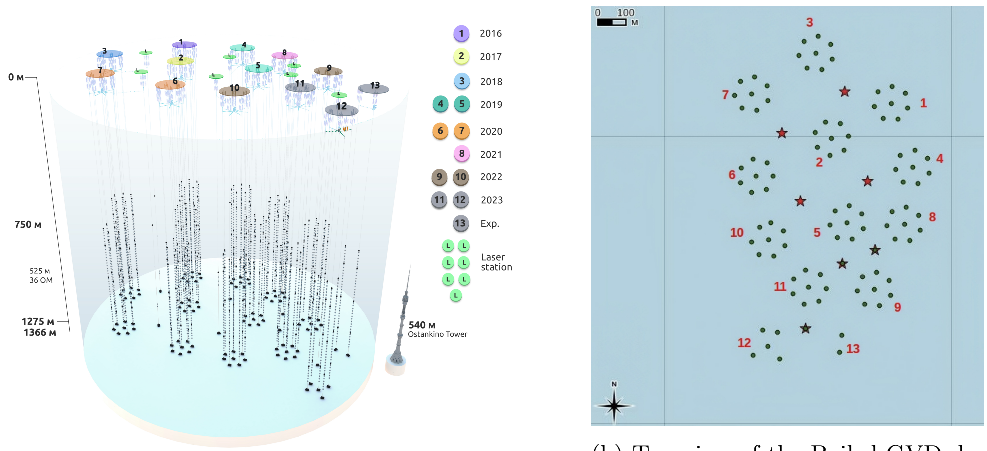
This paper provides a brief overview of the current status of Baikal-GVD neutrino telescope development and its most recent findings related to the study of the diffuse neutrino flux. In Section 2, we present the general scheme of Baikal-GVD. Section 3 briefly describes a brand new software package **N**eutrino **T**elescope **S**imulation (**NTSim**) developed for simulations of physics processes of a neutrino telescope. Lastly, in Section 4, we will present some latest results from Baikal-GVD regarding studies of high-energy diffuse neutrino flux, covering the period from April 2018 to March 2022.

2. THE BAIKAL-GVD NEUTRINO TELESCOPE

The Baikal Gigaton Volume Detector (Baikal-GVD) is situated in the southern region of Lake Baikal, approximately 3.6 km from the shore (51°46′N, 104°23′E). The depth of the lake at the detector location is about 1366 m. The Baikal-GVD OM consists of a sealed, pressure-resistant glass sphere, made of two hemispheres, housing a 10-inch Hamamatsu R7081-100 PMT (35% quantum efficiency at 390 nm), along with its high-voltage power supply and interface electronics.

Additionally, the OM integrates calibration LEDs and a variety of sensors, including an accelerometer/tiltmeter, a compass, a pressure sensor, a humidity sensor, and two temperature sensors. These OMs are mounted on vertical Strings anchored to the lake bed, held taut by a buoy system at the top. Each String carries 36 OMs, with their PMT photocathodes facing downward, spaced 15 m apart, covering an active height of 525 m, starting 90 m above the lake bed. Additionally, each String has three Section Master Modules, each managing 12 OMs (or Sections). These Modules power the OMs and convert PMT signals to digital format at 200 MHz. The Section Master Modules link to the String Module, which distributes power and facilitates communication. Hydrophones on the String help track the OMs' positions, and LED beacons aid in detector calibration (Šimkovic et al., 2021; Aynutdinov et al., 2022).

The OMs are arranged on Strings forming a heptagonal Cluster, with 8 Strings positioned at the center and vertices of the heptagon, each spaced about 60 m apart. The String Modules from each String connect to the Cluster Center, which in turn links to the shore station via an electro-optical cable. The Cluster Center is responsible for synchronizing the Strings, managing cluster-level triggering, and transmitting data to the shore.



(a) Schematic view of the Baikal-GVD detector

(b) Top view of the Baikal-GVD detector

Figure 1: (a) The legend shows the annual progress in the detector deployment. (b) The dots represent the Cluster Strings, the red stars depict Laser stations and the stars with a center dot are ICS.

Clusters are positioned about 300 m apart, measured from their geometric centers. Since 2019, two Clusters have been added annually, except for 2021 when only one was installed. To boost sensitivity to neutrino cascade events, Inter-Cluster Strings (ICS) were introduced in 2022 at the center of each recent triplet of Clusters (Dvornicky et al., 2023a). Monte-Carlo simulations indicated a 24% increase in astrophysical event detection for cascades over 100 TeV (Bardačová et al., 2023). By 2023, three ICS, structurally similar to Cluster Strings, were in place, each equipped with a Laser source for inter-Cluster calibration.

Each Cluster operates autonomously, allowing for individual or multi-cluster joint data analysis. A standard cluster trigger helps suppress background noise from water luminescence and PMT dark current. However, the bandwidth of the underwater network is constrained by the 5.7 Mbit/s speed of shDSL Ethernet extenders per String, limiting data collection. The maximum Cluster response frequency for data transmission to the shore is 200 Hz. To activate a Cluster, two adjacent OMs in the same Section must detect hits within a 100 ns window, with a minimum average hit amplitude of about 3.5 photoelectrons (p.e.) for one OM and 1.7 p.e. for the other (Dzhilkibaev et al., 2022). When a Section Module meets the trigger condition, all Sections of the Cluster record hits over a 5 μsec timeframe. The data is then sent to the shore via a 7 km long fiber-optic hybrid cable at 1 Gbit/s.

LED calibration light sources, emitting at 470 nm with 5 ns pulses, are used to measure signal time delays in OMs. Their intensity varies from a few photons to 10^8 photons per pulse. These pulses form a 15° cone, detectable by OMs up to 100 m away. Each OM contains two upward-facing LED sources. For inter-String time calibration within a Cluster, two horizontal LED matrices with 5 LEDs each are installed in 12 OMs on the central and two outer Strings. The LEDs are evenly spaced in a circle, achieving a time calibration accuracy of about 2-3 ns.

Laser sources in the inter-Cluster spaces are used for time calibration between Clusters. Since 2022, a Laser has been installed on each ICS. This Laser emits a 532 nm pulse for 1 ns, with a maximum intensity of 10^{15} photons. The beam passes through a light guide into a diffuser, creating a quasi-isotropic light source. These Lasers serve not only for time calibration of nearby Clusters but also to analyze and monitor the water optical properties in Lake Baikal's Baikal-GVD area. Consequently, inter-Cluster time synchronization maintains a precision of about 2 ns in measuring the relative response time of OMs across different Clusters, matching the synchronization accuracy within a single Cluster.

3. SIMULATION TOOLKIT

To reconstruct astrophysical neutrino events and model background from atmospheric muons and neutrinos, detailed Monte-Carlo simulations are employed. These simulations estimate the expected rate of astrophysical or background events and optimize the analysis of experimental data. Neutrino events are categorized based on the type of neutrino interaction, which varies with its flavor. A neutrino telescope typically exhibits three distinct responses:

(i) Track-like events arise from the charged-current (CC) interactions of muon neutrinos (ν_μ) or tau neutrinos (ν_τ) that lead to the decay of the tau lepton into a muon. High-energy muons can travel considerable distances, creating extended tracks of Cherenkov photons that may cross more than one Cluster. Through either single-cluster or multi-cluster reconstruction of such track-like events, the neutrino source can be pinpointed with an accuracy of a fraction of a degree. However, the energy of these events is typically reconstructed with an accuracy of 200-300%.

(ii) Cascade-like events occur due to the interaction of an electron neutrino (ν_e) through CC, or via NC interactions for neutrinos of any flavor. These interactions result in the formation of a cascade of Cherenkov photons, originating from hadronic and electromagnetic cascades. The anisotropy of Cherenkov radiation in water enables the reconstruction of the neutrino's arrival direction with an accuracy of several degrees. The precision in recovering the event energy is approximately 10-30%, making cascade-like events useful for studying the energy spectrum of astrophysical neutrino flux.

(iii) Double cascades are initiated by CC interaction of a tau neutrino, followed by the decay of the tau lepton and the ensuing generation of a hadronic or electromagnetic cascade.

The primary method for detecting astrophysical neutrinos is the observation of Cherenkov radiation, emitted when secondary charged particles travel through a transparent medium faster than the phase velocity of light in that medium. This detection principle is foundational for neutrino observatories. At the Baikal-GVD location, the characteristic absorption length is approximately 22.2 m at a wavelength of 488 nm, and the effective scattering length is around 480 m at 475 nm (Balkanov et al., 1999; Avrorin et al., 2012 & Dvornicky et al., 2023b). Both parameters can vary with depth and over time. The large effective scattering length at Baikal-GVD enhances its capability to identify astrophysical neutrino sources. The sequence of hit OMs serves to reconstruct the initial direction of the incident neutrinos, while the integrated charges serve as a metric for the energy of the neutrinos. This approach greatly contributes to the comprehensive study of astrophysical neutrinos and their sources.

The **N**eutrino **T**elescope **S**imulation (**NTSim**) is a brand new software package under development for Monte-Carlo simulation of neutrino events and calculating neutrino telescope responses. NTSim is developed in Python, enhancing user interaction. To speed up simulations, it integrates third-party libraries like NumPy, and Numba, which translates Python code into fast machine code. At its core is Geant4, used for modeling particle passage through matter (Agostinelli et al., 2003; Allison et al., 2006, 2016). The link between Geant4 and NTSim is enabled by g4camp (g4camp), based on the geant4_pybind python package (geant4_pybind). This integration facilitates particle propagation simulations up to 1 PeV in water, accounting for both electromagnetic and hadronic interactions.

The modelling chain in NTSim begins with primary interaction generation via the PrimaryGenerator. A variety of generators are available: The NuGenerator, producing neutrino fluxes according to a given spectrum, varying or fixed arrival directions, energies, and Bjorken variables, and allowing selection of interaction channel (CC or NC); and ToyGen, which creates particles from Geant4's available list. Additionally, the Laser generator simulates monochromatic laser sources, while SolarPhotons follows the solar spectrum in the optical range at Earth's surface. Focusing on the neutrino generator, NuGenerator simulates neutrino interactions with matter and produces primary tracks. Secondary particles are processed by the Propagator module, Geant4 with a pythonized g4camp shell. This simulation yields two datasets: vertices of particle interactions from Geant4, forming particle tracks, where Cherenkov photons are emitted along charged particle tracks as per the Frank-Tamm formula at energies above the Cherenkov threshold; and cascade starters like electrons, positrons, and gamma quanta in the 100 GeV to 100 TeV range, leading to intense electromagnetic showers and subsequent Cherenkov radiation. In NTSim, the Cherenkov photon distribution from electromagnetic cascades is intentionally parameterized rather than using Geant4 for direct propagation. This approach replaces cascade starters with a predefined Cherenkov photon spectrum. This decision is made to avoid the significant computational slowdown that would result from directly propagating Cherenkov light in Geant4.

The generated Cherenkov photons are directed to the RayTracer module, tasked with determining the intersections of photon tracks with the OMs. Upon a photon impacting an OM, both the time and location of the hit are recorded. Subsequently, the average number of photoelectrons produced is calculated. These data points are the primary observables and are instrumental in further analysis of experimental data.

A crucial feature of NTSim is its modular design, which allows users to integrate their own classes into various modules of the modelling chain. This flexibility is particularly useful for evaluating neutrino detection efficiency across different neutrino telescope configurations and identifying the most effective detector geometry. This capability is supported by two specific modules in NTSim: the Telescope module, encompassing the placement of OMs, and the SensitiveDetectors module, facilitating the utilization of various OMs.

NTSim provides additional features, including simulating the detector environment, with the default setting being the waters of Lake Baikal. It also comprises modules for efficiently generating Cherenkov photons and parameterizing electromagnetic showers. A visual interface for displaying simulated events is included, enhancing user interaction. Moreover, NTSim supports operation via a graphical user interface (GUI), offering a more user-friendly experience.

4. FIRST RESULTS

The Baikal-GVD collaboration conducted an analysis of cascade-like events from data collected between April 2018 and March 2022, focusing on high-energy astrophysical neutrino events. Telescope configurations varied over this period: 3 clusters (2018-2019), 5 clusters (2019-2020), 7 clusters (2020-2021), and 8 clusters (2021-2022). To mitigate background noise from water luminescence, the analysis filtered for events with an OM hit multiplicity $N_{\text{hit}} > 7$ across three or more strings and a hit amplitude $Q > 1.5$ p.e. Causality checks were also applied. The analysis utilized a dataset selected under a single-cluster regime.

In the all-sky event analysis, additional criteria were used to reduce atmospheric muons, including energy thresholds $E > 70$ TeV and hit multiplicity $N_{\text{hit}} > 19$. This stringent selection process yielded 16 events for further examination. Of these, 8.2 ± 2.0 events were predicted to be background-related, comprising 7.4 atmospheric muon events and 0.8 atmospheric neutrino events. The remaining 5.8 events aligned with the best fit for astrophysical neutrino flux. Factoring in both systematic and statistical uncertainties, the significance of the astrophysical neutrino flux surplus over the background was estimated at 2.22σ. This analysis led to the null-cosmic hypothesis being dismissed at a 97.36% confidence level (C.L.) (Allakhverdyan et al., 2023a).

The analysis prioritized upgoing events to significantly reduce atmospheric muon background, enabling less stringent selection criteria. Baikal-GVD cascade-like events were chosen with energy $E > 15$ TeV, hit multiplicity $N_{\text{hit}} > 11$, and a zenith angle of arrival $\cos\theta < -0.25$. This strategy led to the identification of 11 events. The projected atmospheric background for these events was 3.2 ± 1, comprising 2.7 events from atmospheric conventional and prompt neutrinos, and 0.5 events from misreconstructed atmospheric muons. After considering both systematic and statistical uncertainties, the significance of the excess events was estimated at 3.05σ, leading to the null-cosmic hypothesis being rejected at a 99.76% C.L. (Allakhverdyan et al., 2023a). These below-the-horizon events were instrumental in characterizing the diffuse astrophysical neutrino flux. The adopted model represented an isotropic single power law for the diffuse astrophysical neutrino flux, presuming equal quantities of neutrinos and antineutrinos, as well as uniform neutrino flavors at Earth:

$$\Phi_{astro}^{\nu+\bar{\nu}} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0} \right)^{-\gamma_{astro}} \tag{1}$$

in units of GeV^{-1} cm^{-2} s^{-1} sr^{-1}, where $E_0 = 100$ TeV. The binned likelihood method with Poisson statistics was applied. This approach allows us to extract the parameters of normalization $\phi_{astro} = 3.04^{+1.52}_{-1.21}$ at $E_0 = 100$ TeV and spectral index $\gamma_{astro} = 2.58^{+0.27}_{-0.33}$ (Allakhverdyan et al., 2023a). The best-fit parameters and 68% C.L. contours together with the results from other neutrino telescopes are presented in Figure 2. The Baikal-GVD extracted parameters of the diffuse astrophysical neutrino flux are consistent with the IceCube and ANTARES measurements.

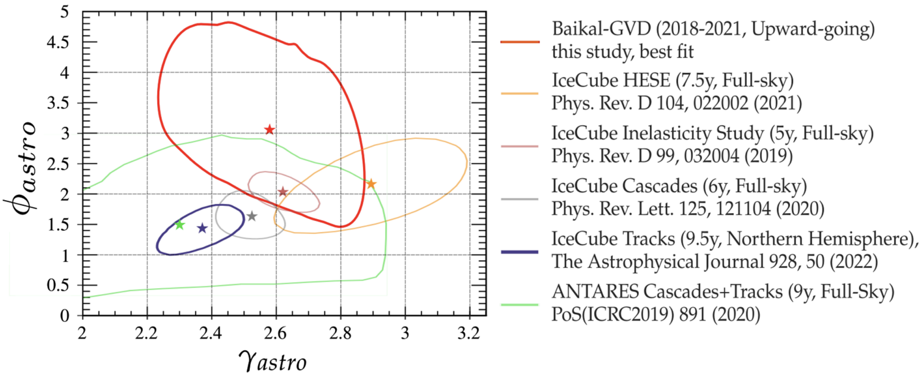


Figure 2: The best fit parameters and the contours of the 68% confidence region (red curve) for the single power law hypothesis obtained in the upward-going cascade analysis of the Baikal-GVD data. The best fit results of IceCube and ANTARES are also presented (Aartsen et al., 2019, 2020; Abbasi et al., 2021, 2022a; Albert et al., 2018 & Fusco et al., 2021).

Figure 3 depicts the sky map of Baikal-GVD events, showcasing the regions of angular uncertainty (50% and 90%) for cascade events from the all-sky analysis via solid lines, and for upgoing events via dashed lines. The full list of cascade-like events with their parameters can be found in the Baikal-GVD publications (Allakhverdyan et al., 2023a, 2023b). Notably, the two events (GVD190523CA and GVD210418CA) that are represented in both samples are also indicated by dashed lines. The grey dots represent blazars from the 8 GHz very-long-baseline interferometry (VLBI) sample with flux densities above 0.33 Jy. This sky map includes several areas of interest. First, three events (GVD190216CA, GVD190604CA and GVD210716CA) located near the Galactic plane with ellipses of 90% uncertainty of which intersecting to form a triplet. This alignment is particularly captivating, as it implies a potential correlation between the events in the Baikal-GVD triplet and the highest-significance Northern hot spot in the IceCube 7-year sky map (Aartsen et al., 2017). This convergence of events may indicate noteworthy activity in this specific area of the Galaxy. Notably, the well-known galactic sources of high-energy radiation LS I +61 303 and Swift J0243.6+6124, fall within the intersection of two events from the triplet (GVD190216CA and GVD190604CA), adding further interest to this region (Allakhverdyan et al., 2023b).

The binary system LS I +61 303 comprises a massive star and a compact object, most likely a pulsar, and is located approximately 2.6 ± 0.3 kiloparsecs (kpc) from the solar system (Gaia Collaboration, 2018). This system is noted for periodic powerful emissions observed across a wide range of energies, from radio to TeV. Additionally, the galactic X-ray pulsar Swift J0243.6+6124 is situated in the same area of the sky map, at a distance of 2-6 kpc. This source was first discovered in 2017 (Cenko et al., 2017; Kennea et al., 2017). This source was initially discovered in 2017 and is presently recognized as the only detected pulsating superluminous X-ray source within the Galaxy.

The Baikal-GVD events appear to show potential associations with extragalactic objects, particularly four blazars with a VLBI flux density at an 8 GHz frequency

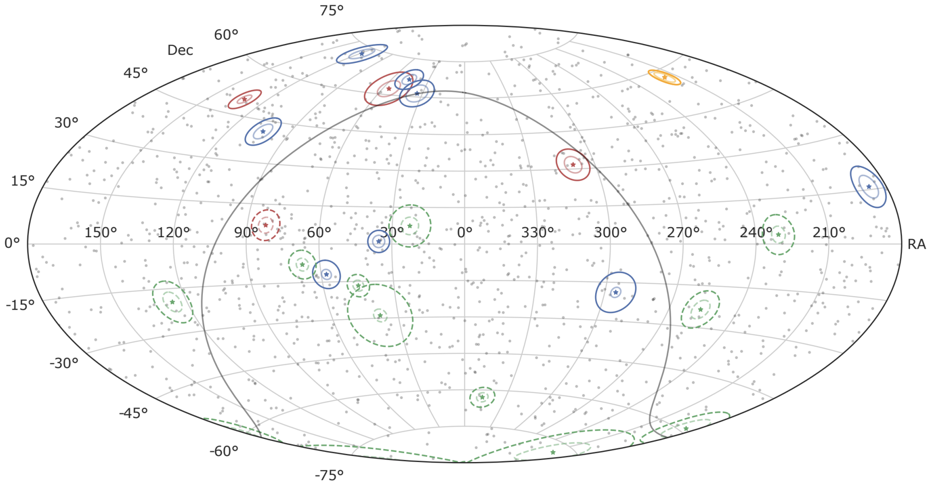


Figure 3: The sky map for Baikal-GVD cascade-like high-energy events (equatorial coordinates). Stars: the best fit positions of events. Ellipses: event uncertainty regions (90% and 50%). Dashed lines represent upgoing events as well as solid lines present cascades from all sky analysis. Colour represents energies of the events: green is below 100 TeV, blue is between 100 TeV and 200 TeV, red is between 200 TeV and 1000 TeV, orange is above 1 PeV. Grey dots: positions of 8 GHz VLBI blazars with flux densities above 0.33 Jy. The Galactic plane is depicted as the grey curve.

exceeding 1 Jy. Of particular interest, three of these blazars, 2023+335, 2021+317, and 2050+364, are situated in close proximity to the GVD210409CA event. Notably, 2023+335 stands out with the highest brightness among these blazars. In addition, the fourth blazar, 0529+075, is potentially associated with the GVD210418CA event.

Additionally, it has become possible to correlate powerful radio flares from blazars with the Baikal-GVD events. The most exciting coincidence is the blazar TXS 0506 + 056 ($z = 0.34$, average 0.5 Jy at 8 GHz), which is spatially coincident with the GVD210418CA event (Allakhverdyan et al., 2024). Prior to the Baikal-GVD analysis, the IC170922A event of the IceCube had already been associated with the TXS 0506 + 056 gamma-ray flare in 2017 (Aartsen et al., 2018; IceCube Collaboration, 2018). As shown in Figure 4, the neutrino events from IceCube and Baikal-GVD coincided with the onset of prominent radio flares. This observation can further validate the statistical connection between high-energy neutrinos and compact radio-loud structures in blazars (Plavin et al., 2020). Research in this area could shed light on the processes occurring in distant astrophysical objects and the mechanisms leading to the acceleration of particles to ultra-high energies.

The LIGO/Virgo observatories discovered gravitational waves from a neutron star merger in 2017 (LIGO/Virgo Collaboration, 2017). Also, Fermi-LAT and INTEGRAL recorded a short gamma-ray burst, which indicates the acceleration of particles by the source (Savchenko et al., 2017). The exact location of the event was determined after the merger by optical detection. The Baikal-GVD collaboration searched for high-energy neutrinos in the range 1 TeV-100 PeV from this event. After recording a gravitational wave for 14 days, no neutrinos coinciding in direction with the source

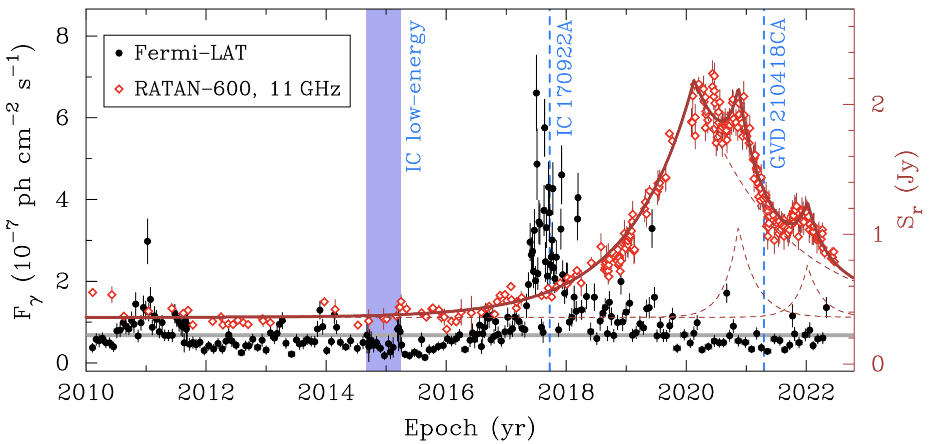


Figure 4: Radio and gamma-ray light curves of TXS 0506 + 056. Black dots: Fermi LAT adaptive binning light curve of the gamma-ray source 4FGLJ0509.4+0542 positionally associated with TXS 0506 + 056. Grey horizontal line indicates the median gamma-ray flux. Empty red diamonds: RATAN-600 light curve at 11 GHz. The radio light curve is decomposed by three radio flares depicted by dark-red dashed lines, the sum of which is represented by a thick line. Neutrino-associated events are indicated by vertical dashed lines.

were detected. Upper limits on the neutrino fluence were obtained (Avrorin et al., 2018) with a 90% confidence level from GW170817, assuming an E^{-2} neutrino energy spectrum. Another interesting source traced by the Baikal-GVD collaboration is the magnetar SGR 1935+2154. After analysis, the upper limit on the number of events was found to be 5.91 at 90% confidence level (Allakhverdyan et al., 2022).

There is also an exchange of neutrino alerts between neutrino telescopes. One example of such interaction is the exchange between ANTARES and Baikal-GVD starting in 2018. An example of such an exchange is the work (Alves Garre et al., 2021) where the limits of the astrophysical fluence of neutrinos were presented, assuming a E^{-2} neutrino spectrum.

5. CONCLUSION

The Baikal-GVD project is the largest neutrino telescope in the northern hemisphere. Its inaugural Cluster was deployed in 2016, and the detector's active volume has increased annually since. As of January 2024, Baikal-GVD consists of 12 Clusters with 3456 OMs, spanning an instrumented volume of about 0.5 km^3 for cascade-like events above 100 TeV. The telescope's modular structure enables ongoing data acquisition during expansion. The investigation of the diffuse astrophysical neutrino flux relies on analyzing cascade-like events detected in a single-cluster mode from April 2018 to March 2022. This analysis identified an excess of 3.05σ above expected atmospheric background events, marking the first confirmation of IceCube's observation of the diffuse astrophysical neutrino flux with significance just over 3σ. A statistical analysis was conducted to correlate neutrino events with astrophysical sources like LS I +61 303, Swift J0243.6+6124, and TXS 0506 + 056. While the existing data does not conclusively identify the Baikal-GVD events originating from these sources, it does indicate the potential for further exploration of specific regions of the sky map. Future expansions of Baikal-GVD aim to reach 1 km^3 with about 6000 OMs by 2027/2028. Additionally, a next-generation telescope project for 2025 focuses on identifying astrophysical neutrino sources.

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