JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Visualisation of Astrophysical Data for Baikal-GVD Neutrino Telescope

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Abstract

Baikal-GVD is the biggest neutrino telescope in the Northern Hemisphere. Its main goal is to detect high-energy neutrino events which are one of the sources of information about far cosmic objects. Since 2020 Baikal-GVD has been participating in multi-messenger program. This program involves exchange of alert events between different astrophysical experiments. Alert is a short message with essential information, that is formed when a potential signal from an astrophysical source is found by data analysis algorithms.

The main goal of the conducted work was to create algorithms for reading and visualisation of the data from internal Baikal-GVD alerts as well as the data from Baikal-GVD follow-ups of the other astrophysical experiments. This graphic representation could provide a better view on the potential astrophysical sources of the neutrinos.

Introduction

Modern astronomy and astrophysics aim to study the astrophysical objects with help of the different types of signals incoming from them, such as photons, neutrinos, cosmic rays and gravitational ways. In order to achieve the goals of the multi-messenger (MM) astronomy, it is necessary for the different kinds of experiments to regularly exchange data with each other. That can be done with alerts messages.

Alert is formed when a potential neutrino/EM/gravitational wave event is found by algorithms of MM experiments. It contains essential information about the detected event such as sky coordinates, date, time of the detection, number of false events per year, energy etc. This message can be sent to the international networks such as Gamma-Ray Coordinates Network [ссылка] and it can report about the activity of astrophysical sources. Currently Baikal-GVD processing system receives and follows up external alerts automatically. However Baikal-GVD internal alerts and results of follow-up analysis are available only the Baikal-GVD working group.

To provide the better understanding of workflow of Baikal-GVD alert system and to research the potential astrophysical neutrino sources it is preferably to visualise the alerts.

This work deals with both types of alerts: internal Baikal-GVD alerts and external messages coming from the other experiments such as IceCube neutrino telescope, FERMI gamma-ray telescope and LIGO/VIRGO/KAGRA gravitational observatories network. During the course of the program the methods of data visualisation such as Python3 libraries as well as Grafana software were studied. Also different kinds of databases and their applications were explored.

Chapter 1

Skymaps plotting for Baikal-GVD

1.1 Coordinate systems

In the beginning of our work we needed to study skymaps can be visualised in general and what kinds of astronomical coordinate systems are used at this time.

- **Horizontal coordinate system:** The location of the object can be described by: Altitude (alt.) is the angle between the object and the observer's local horizon. For northern hemisphere , it is an angle between 0° and 90° and between 0° and -90° for southern hemisphere. Azimuth (az.) is the angle of the object around the horizon, usually measured from true south and increasing westward.
- **Equatorial coordinate system:** The declination δ (Dec) measures the angular distance of an object perpendicular to the celestial equator, positive to the north, negative to the south. The right ascension α (RA) measures the angular distance of an object eastward along the celestial equator from the vernal equinox to the hour circle passing through the object.
- **Ecliptic coordinate system:** The position of the object can be described by two angels and distance: Ecliptic longitude (l) measures the angular distance of an object along

the ecliptic from the primary direction. Ecliptic latitude (b), measures the angular distance of an object from the ecliptic towards the north or south ecliptic pole. The north ecliptic pole has a celestial latitude of +90°, the south ecliptic pole has a celestial latitude of -90°. Distance (heliocentric r, geocentric Δ), usually astronomical units are used as distance units.

- **Galactic coordinate system:**The galactic coordinates use the Sun as the origin. The location of the object can be described by: Latitude (symbol b) measures the angle of an object northward of the galactic equator as viewed from Earth. Longitude (symbol l) measures the angular distance of an object eastward along the galactic equator from the Galactic Center.

1.2 Catalogs of the potential neutrino sources

The origin of astrophysical neutrino is still under study. The sources of cosmic rays are accelerating protons to very high energies, which collide with other particles or photons and generate pions and hence produce neutrinos. The IceCube has registered neutrino with high significance only from two sources of astrophysical neutrino [link]. It's also known about existence of astrophysical diffuse neutrino flux which was observed both Baikal-GVD and IceCube. To follow-up potential neutrino sources five catalogs were formed for Baikal-GVD during this work. These catalogs include not only well-known astrophysical objects such as blazars and Seyfert galaxies but also catalogs with events published by Baikal-GVD, IceCube and HAWC experiment:

- "Short" catalog with some of the most active astrophysical sources. It represents the a shortlist of highly suspected neutrino sources, with a focus on point-like steady and slowly variable sources such as brightest nearby Seyfert galaxies,

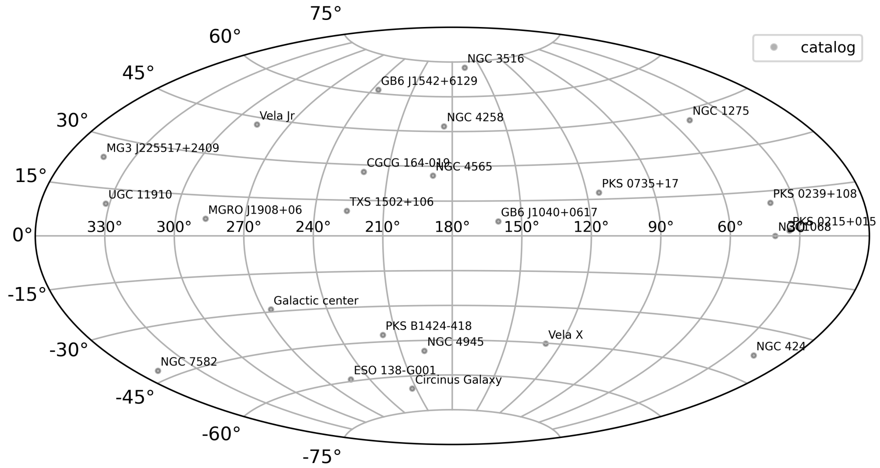

Figure 1.1: The "short" catalog

some of the most prominent active galactic nucleus, supernovae remnants. It consists of 24 objects.

- Published Baikal-GVD cascade events
- Recent IceCube alerts posted on the NASA Global Coordinates network website
- Published IceCube neutrino sources (IceCat-1 catalog)
- Extended catalog with different kinds of other neutrino sources such as blazars, AGNs, supernovae, etc. published by other experiments. It contains 762 ogbjects.

Some of the plotted catalogs are presented on the figures 1.1, 1.2, 1.3, 1.4. The data were read and plotted with the usage of Python3 libraries such as pandas, numpy, matplotlib, plotly, astropy.

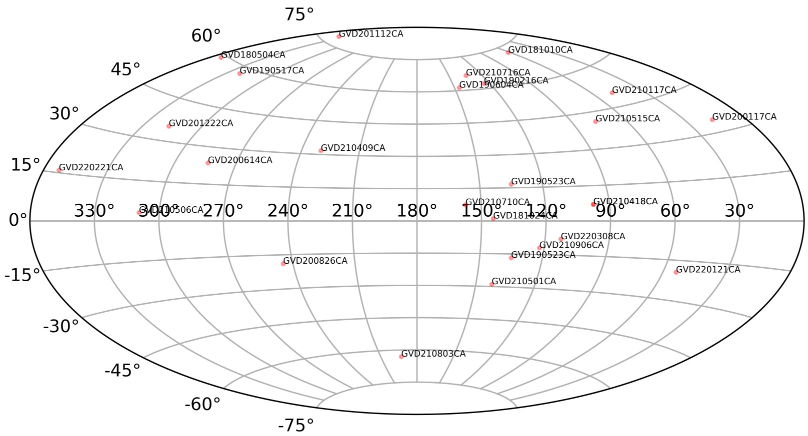

Figure 1.2: The published Baikal-GVD potential neutrino candidates

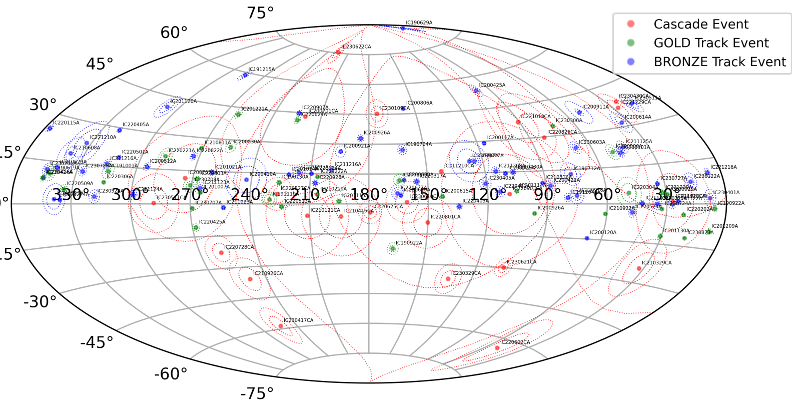

Figure 1.3: Recent IceCube alerts posted on the NASA Global Coordinates network website. Positions in equatorial coordinates (dots) with their errors (dotted lines) are shown

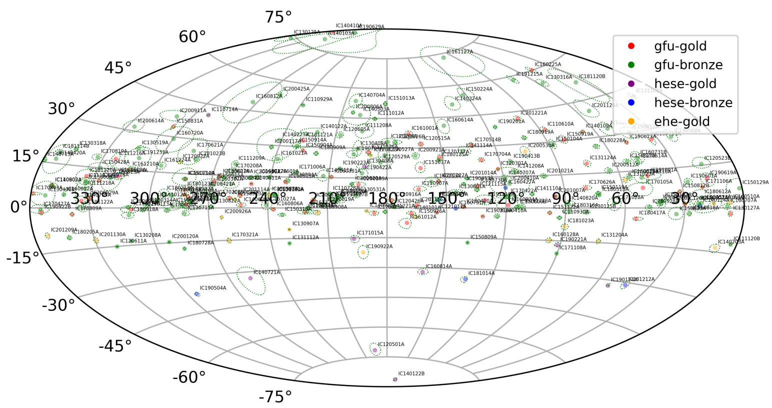

Figure 1.4: IceCat catalog. Positions in equatorial coordinates (dots) with their errors (dotted lines) are shown

1.3 Databases

Baikal-GVD produces large data flow every day. To keep Baikal-GVD data and also data from other telescopes which we need to follow up MariaDB and Influx databases are used. In addition to these databases Baikal-GVD plans to start to use the MongoDB database. Mongo DB is convenient to keep json files which are the modern format of astrophysical data. During this program we used all of the above databases.

Both internal alerts from the Baikal-GVD experiment and external alerts from other experiments should be accessible for the Baikal-GVD participants from their local computers or from the virtual machines at any time. In order to provide the desired accessibility all of the alerts are stored in the databases. Internal alerts are stored in the the MariaDB database, IceCube, Gamma-Ray Bursts (GRB), International Gravitational Waves Network (IGWN) alerts are in the InfluxDB database.

It was decided to store the potential neutrino sources catalogs in the MariaDB, so a suitable table within the existing database was created and the catalogs were uploaded there. Now they are accessible for every collaboration member. The visualisation of

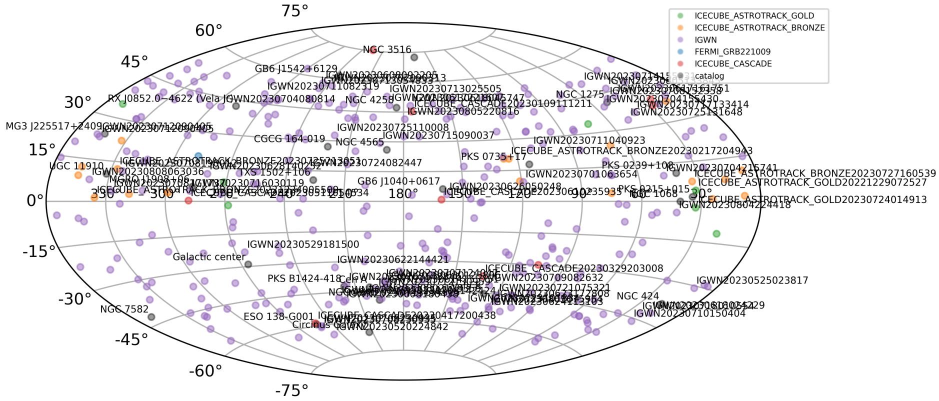

Figure 1.5: Incoming alerts from InfluxDB without error of positions

the and incoming alerts from IceCube collaboration, gravitational waves observatories (IGWN) and the first catalog of the potential neutrino sources (figure 1.5) is shown below.

1.3.1 LIGO alerts and MongoDB

It's important to mention that Baikal-GVD experiment carries out follow-ups of the alerts from the LIGO scientific collaboration which deals with the detection of the gravitational waves. This kind of alerts has a structure that differs from the Baikal-GVD and IceCube alerts.
Firstly LIGO incoming alerts were stored in the InfluxDB without some of the information due to the alert properties. Thus in order to store this alerts more convenient the possibility of the storage within the MongoDB was considered. The MongoDB was chosen because it provides opportunities to write and store files with the similar characteristics as LIGO alerts, in particular JSON format files. During our internship the features of working with Mongo database were studied, the reception of alerts to the local machine and their storage in the database were adjusted.
In the process of doing this part of the work the following Python3 libraries were used: mysql-connector-python, influxdb-python, gcn-kafka, pymongo.

The potential sources of the gravitational waves events do not have a point-like coordinates like neutrino sources. They represent a large area with different values of the probability of the presence of sources of gravitational waves.
Therefore it was required to apply a different approach to the plotting routine. The result is shown on the figure 1.6. The following Python3 libraries were used: base64decode, astropy, astropy.healpix.

1.4 Visualisation of the internal alerts and coincidences with incoming alerts in processing

The main goal of the work was to provide scripts for visualisations of the two types of alerts. These scripts will be used in automatic

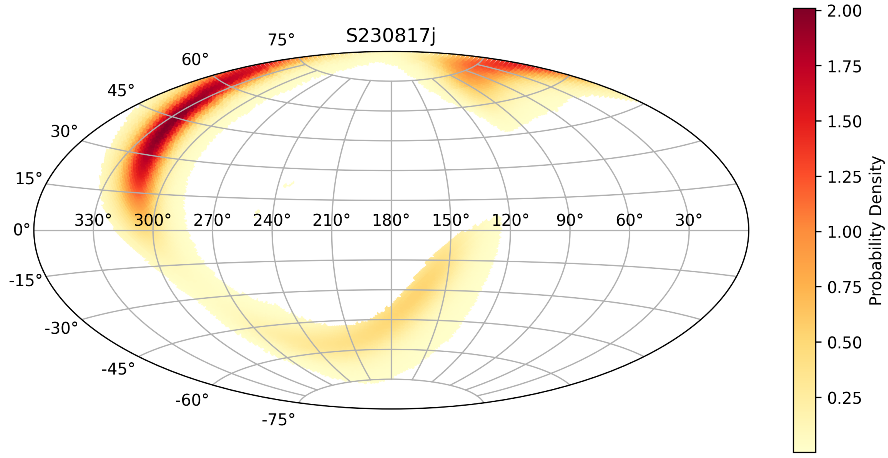

Figure 1.6: Visualisation of the LIGO S230817j event

processing of Baikal-GVD and will allow to visualise data about possible astrophysical events in real time. Currently they are a part of Baikal-DP repository which is located on gitlab.jinr.ru and written with Python.
Firstly, the last internal alert which comes as the result of the data analysis and event reconstruction process are needed to plot. For better understanding of the nature of internal alerts and its posiible sources it was decided to plot the last alert on the skymap with all of the other internal alerts (mentioned in the section 1.2) and the first catalog of the potential neutrino sources (mentioned in the section 1.1).
Secondly, plotting the potential coincidence with external alerts is necessary. These coincidences are the results of work of the alert-searching program which is an integral part of the data analysis process. The search for coincidences is carried out with IceCube neutrino, Fermi telescope GRB and LIGO gravitational wave alerts. The result of the plotting process is a picture of the external alert, internal Baikal-GVD neutrino candidates (or several events) that has coincidence with the external one and the first catalog of the potential neutrino sources (mentioned in the section 1.1). Both types pictures are plotted with the galactic plane projection. It should be mentioned that all Baikal-GVD

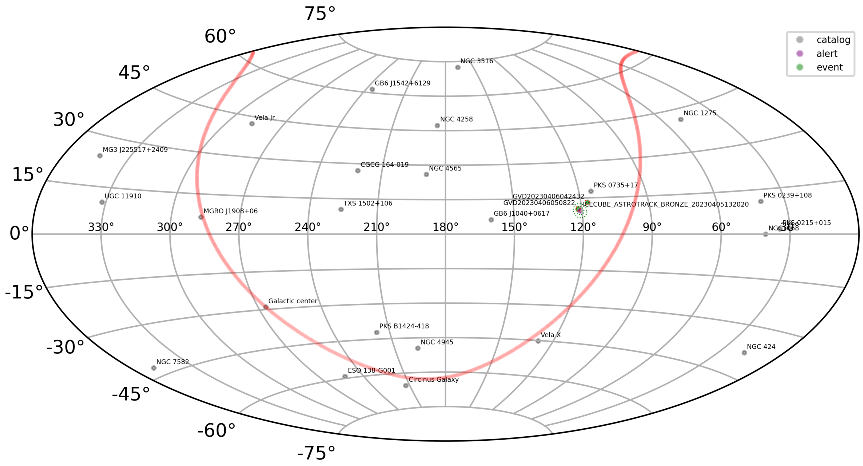

Figure 1.7: Baikal-GVD potential coincidences with IceCube alert. Baikal-GVD events were evaluated as background.

neutrino-like events shown in the pictures were evaluated as background events. Some of the the results are show on the figures 1.7, 1.8, 1.9.

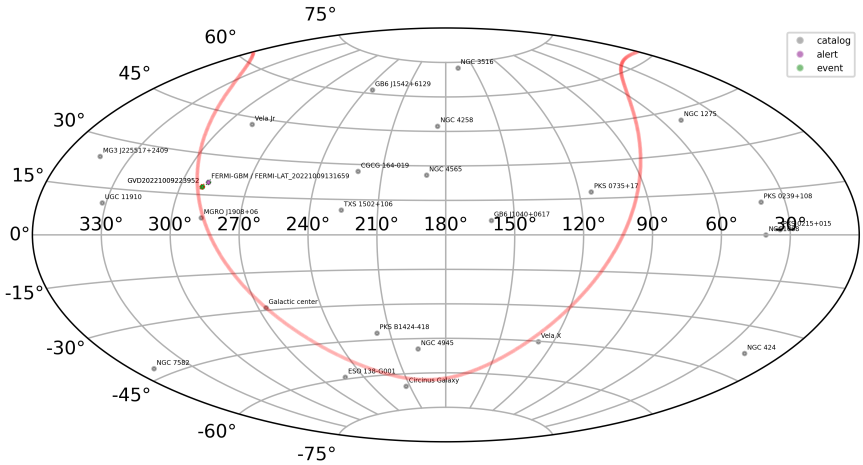

Figure 1.8: Baikal-GVD potential coincidence with Fermi GRB alert. Baikal-GVD event was evaluated as background.

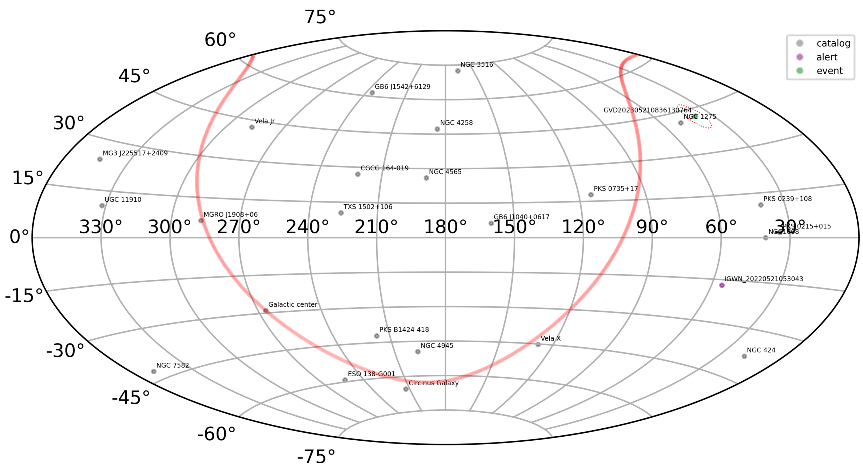

Figure 1.9: Baikal-GVD potential coincidence with gravitational waves alert. Baikal-GVD event was evaluated as background.

1.5 Visualisation with Grafana

Currently the visualisation discussed above allows to attach skymaps with potential neutrino events via e-mail as well as text files about a potential Baikal-GVD alert or a coincidence with external alerts. But in future we need to store and show such images in convenient for users platforms. Over the course of the work several methods of data storing and visualisation were discussed. One of them was the open observability platform Grafana which provides tools for quick and illustrative representation of the data of interest, which can be accessible for the interested group of people. Grafana can plot data from database in visualise it in real time. It was assumed that this software can be a suitable instrument for displaying of the internal and external alerts. In MariaDB was created a table for storing .png pictures that we have plotting in the course of the work, this table was connected with Grafana and several pictures were displayed. However, in order to fully meet the visualisation goals, some technical background work should be done in the first place. It was decided to postpone this task to the future.

On the figure 1.10 the created Grafana dashboard and some of the catalogs.

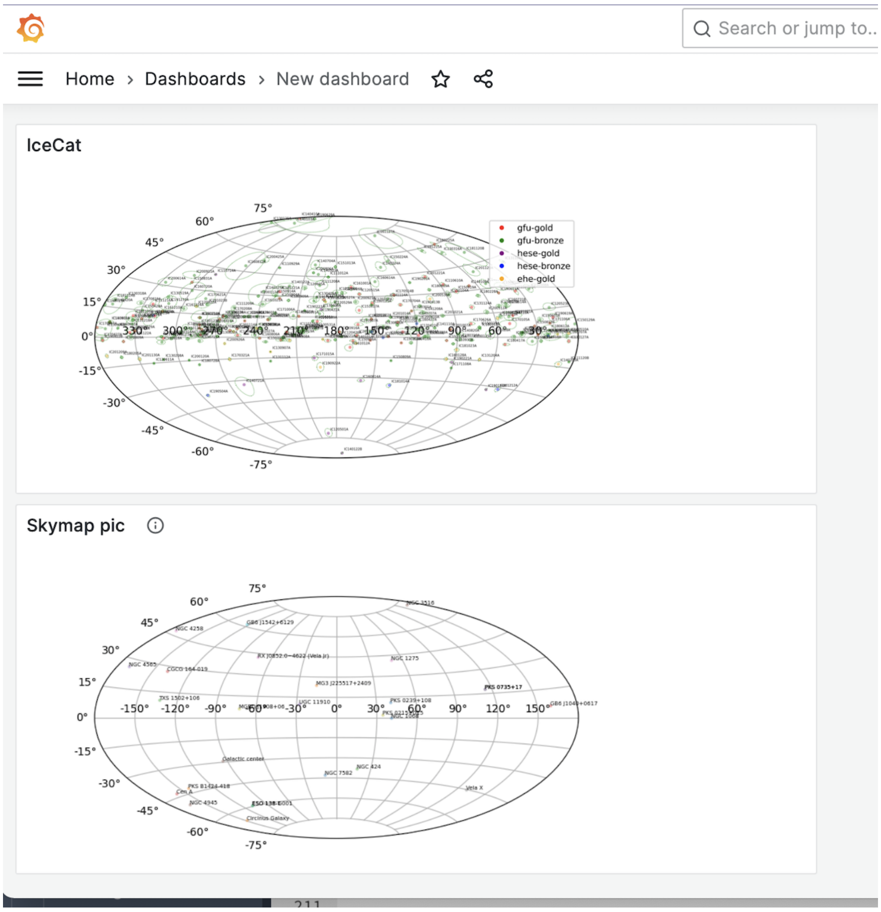

Figure 1.10: Grafana dashboard

1.6 Conclusion

The Baikal-GVD alert system was launched at the beginning of 2021. There are alerts for muon neutrinos (long upward-going track-like events) and all-flavour neutrinos (high- energy cascades). Apart from generation of own alerts Baikal-GVD follows up alerts from other multi-messenger experiments such IceCube, FERMI, LIGO, VIRGO etc. The Baikal-GVD data processing final stage inform Baikal-GVD working group if there are internal alerts or external alerts. This information needs to be plot using modern astrophysical Python libraries and catalogues of astrophysical objects. It can help to understand the nature of potential neutrino events.

In this work the different astronomical coordinates systems were described, the catalogs of the potential astrophysical neutrino sources were formed and they were plotted on the skymap in equatorial coordinates. Ways of working with different databases were studied and later on the databases were used to read and plot data from them. Images of internal and external alerts were obtained. Gravitational waves alerts were studied, stored in the MongoDB database and plotted on the skymap.

Finally, two types of the pictures were obtained: the visualisation of the very last internal alert with all of the old internal alerts along with the first catalog and the visualisation of the external alert, internal Baikal-GVD event (or several events) that has coincidence with the external one and the first catalog. These visualisation methods are available on a Baikal-GVD repository and they are will be used in Baikal-GVD data processing system.

Some of the subsequent goals include the optimisation of the alerts storage, the implementation of the Grafana software and more a more thorough study of the mechanisms of neutrino formation in astrophysical sources.

Also during the program articles on methods of the searches for coincidences in the multimessenger astronomy, articles about the results published by other neutrino experiments such as Ice-

Cube and KM3NeT, articles about the mechanisms of neutrino production in different astrophysical sources were studied [3] [4] .

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