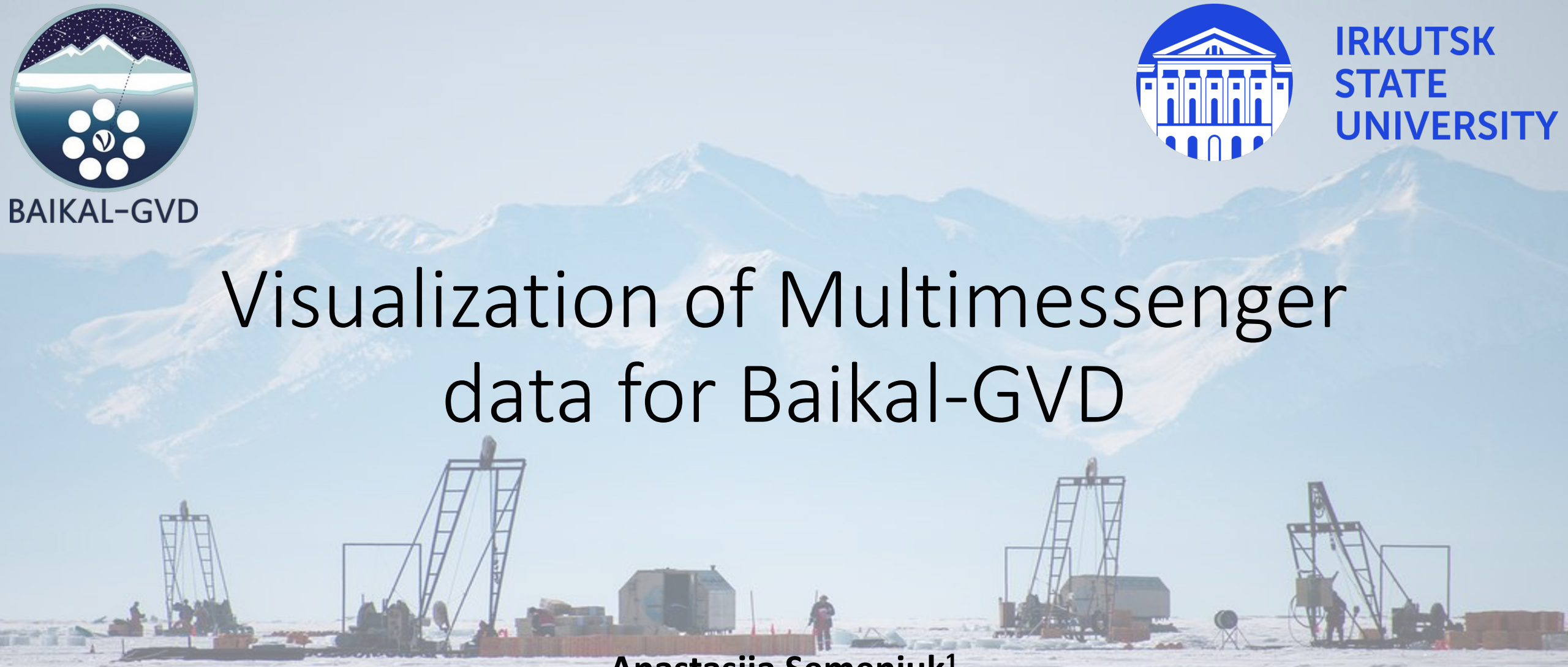

Visualization of Multimessenger data for Baikal-GVD

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On behalf of the Baikal-GVD collaboration

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5. Baikal-GVD alert system
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Tasks

1. Selection of the catalogs for creation of the potential astrophysical neutrino sources list for further use and testing
2. Soft development for work with databases
3. Development of soft for visualization of incoming alerts and display of potential matches with them, as well as Baikal-GVD internal alerts

Baikal-GVD Neutrino Telescope

Goal: search for and registration of high-energy neutrinos of cosmic origin

Detection method: registration of Cherenkov photons emitted during interactions

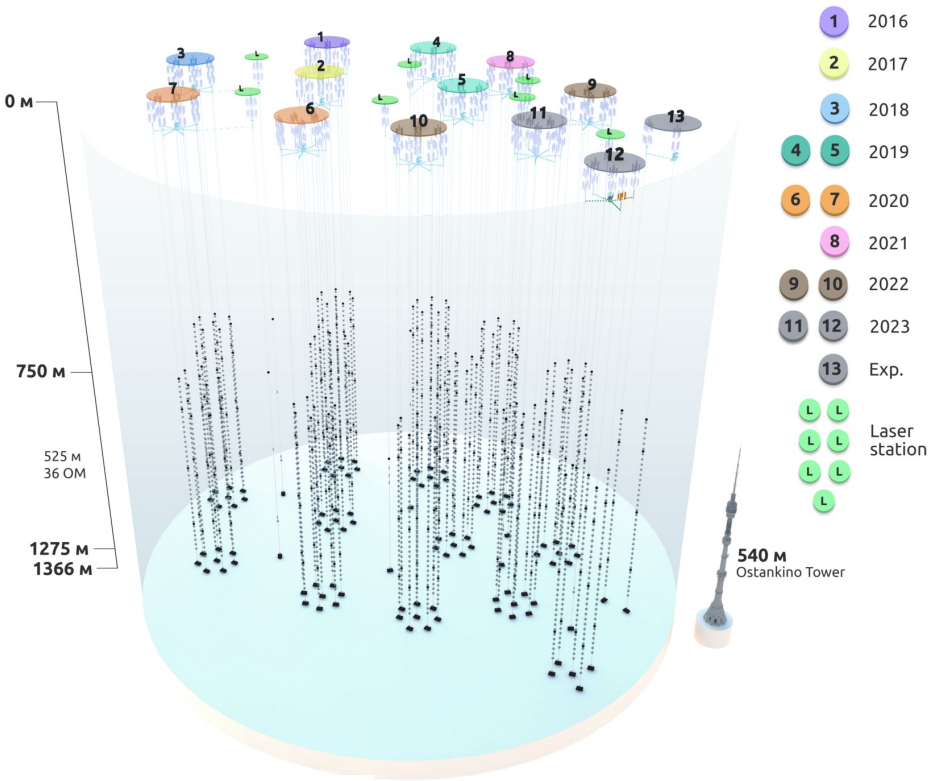
For 2023:

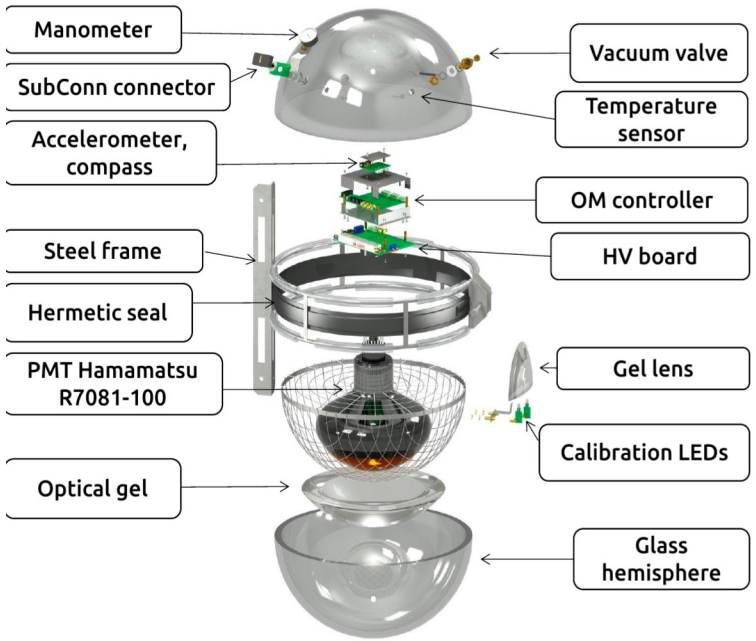
-12 clusters

- 8 strings in each cluster

- 36 photomultipliers on each string

- 3456 total optical modules number

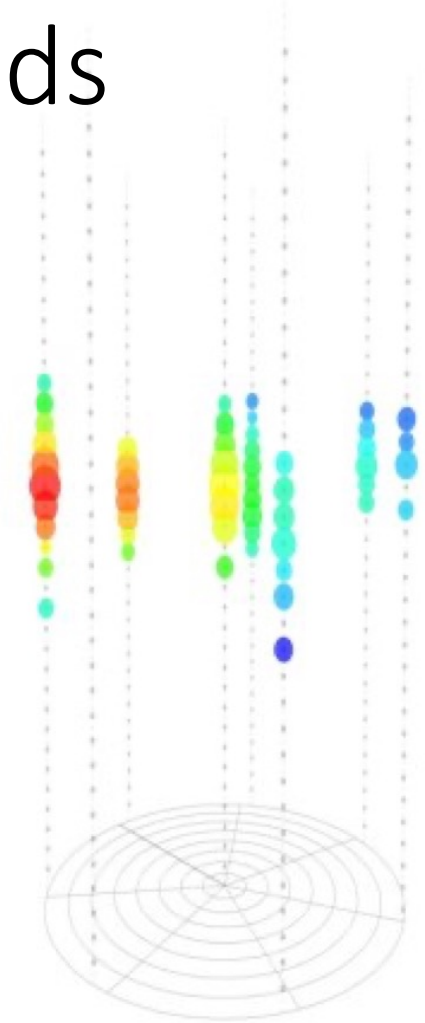




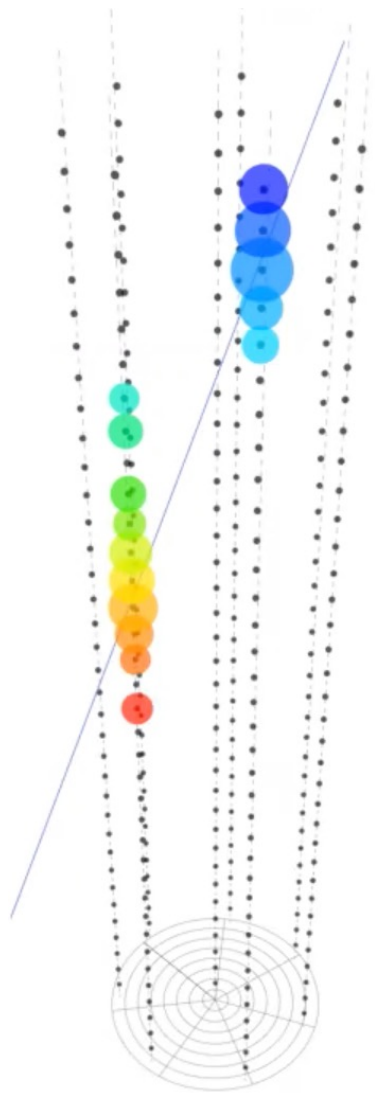
Events reconstruction methods

1. Track-like measurements - a method for selection of muon neutrinos with very good accuracy of determining the direction to the source in the sky. Angular resolution ~ 1 deg.

2. Cascade measurements performed with help of particles from the interaction of neutrinos of any flavour. Angular resolution 2-4 deg.

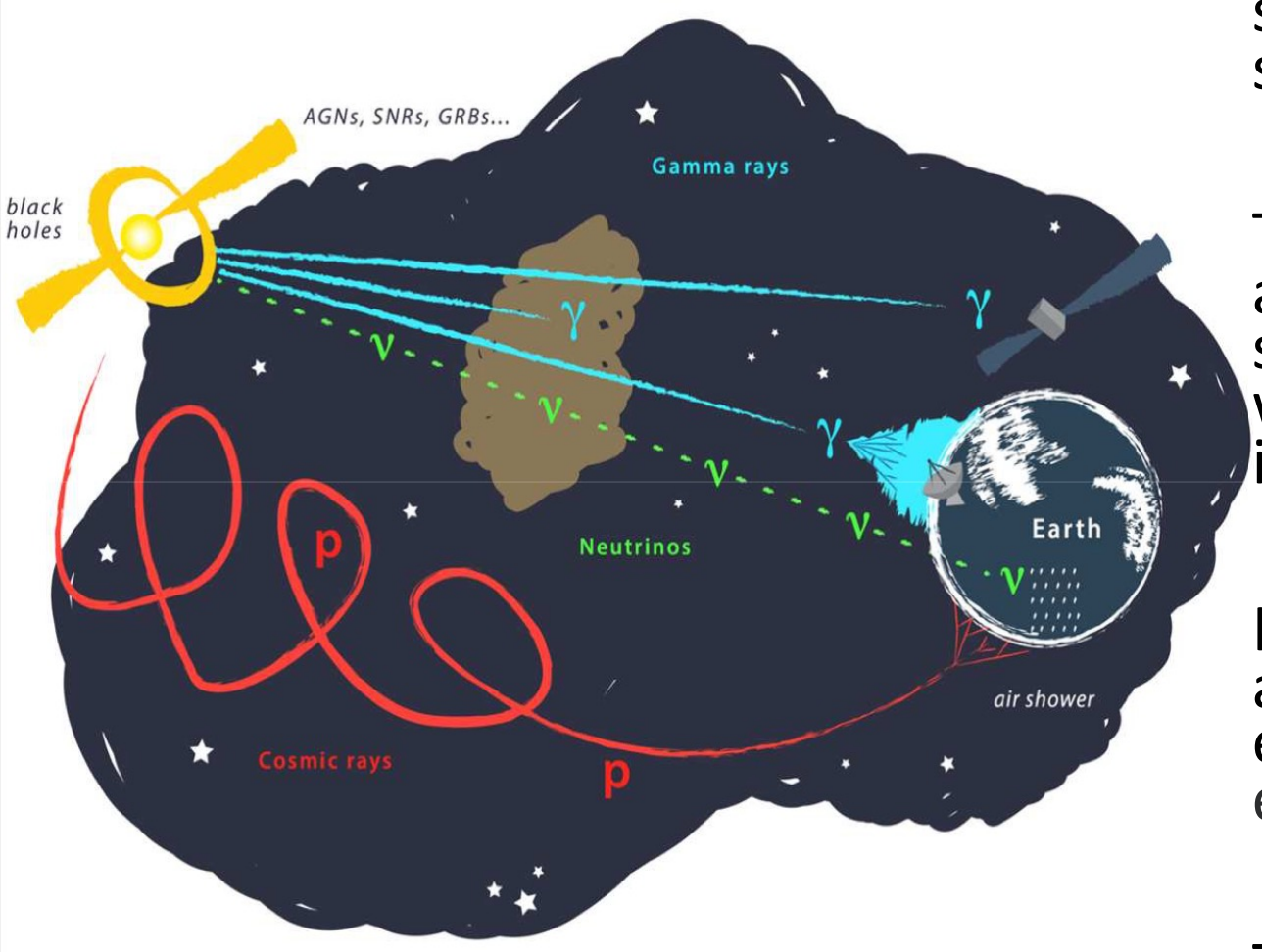


Cascade event



Track event

Multimessenger astronomy



Modern astrophysics strives to study deep space objects using various types of incoming signals.

The main idea of multimessenger (MM) analysis is to search for the correlation of signals from a source in time and direction with help of different astronomical instruments.

In order to achieve the goals of MM astronomy, regular data exchange between experiments is necessary, especially in real time.

This can be performed with alert messages.

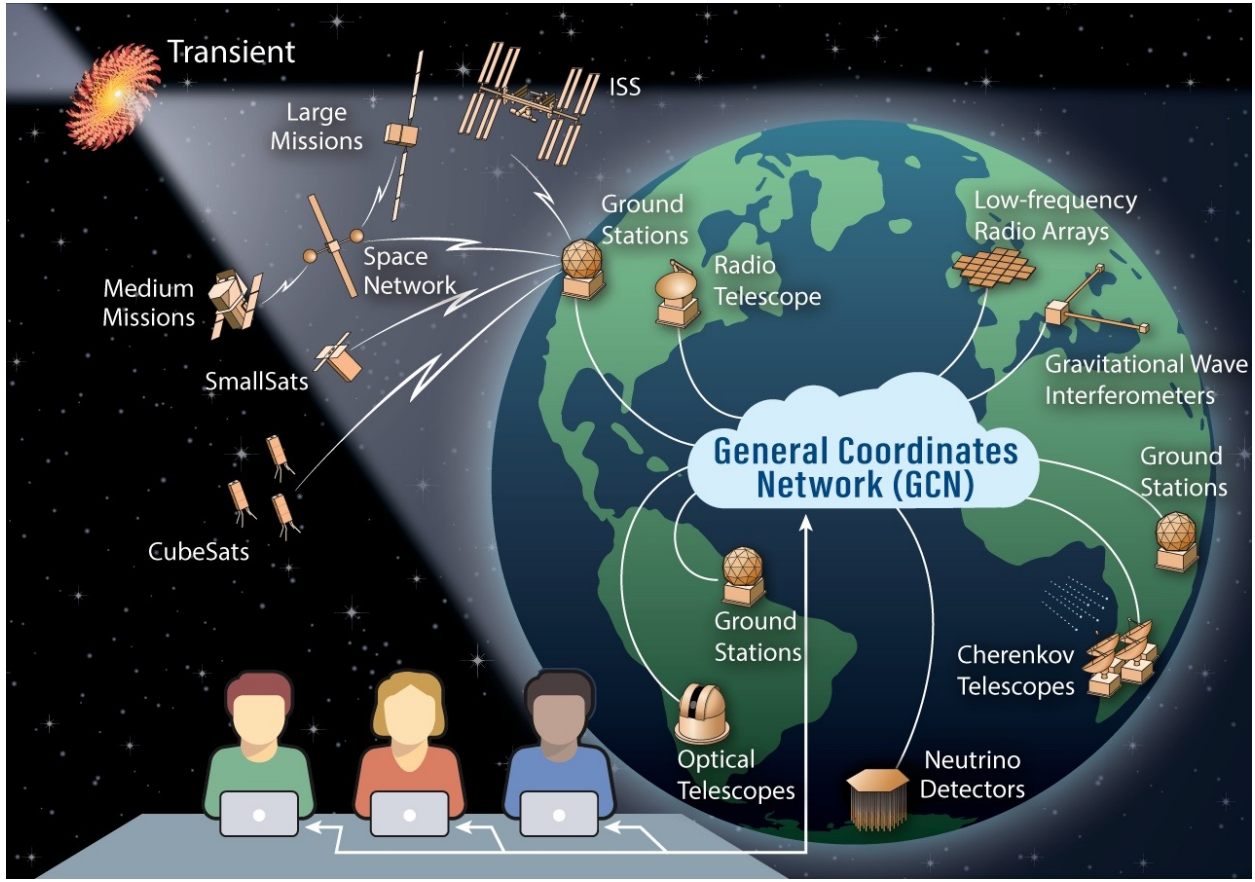
Baikal-GVD alert system

Since 2020 Baikal-GVD has been participating in the multichannel astronomy program.

Alert is a short message containing the necessary information about the event.

The telescope's data processing system receives and follows up alerts automatically.

Goal: search for coincidences in space and time between external alerts and Baikal-GVD events.



Potential astrophysical neutrino sources catalogs

The origin of astrophysical neutrinos is still under study.

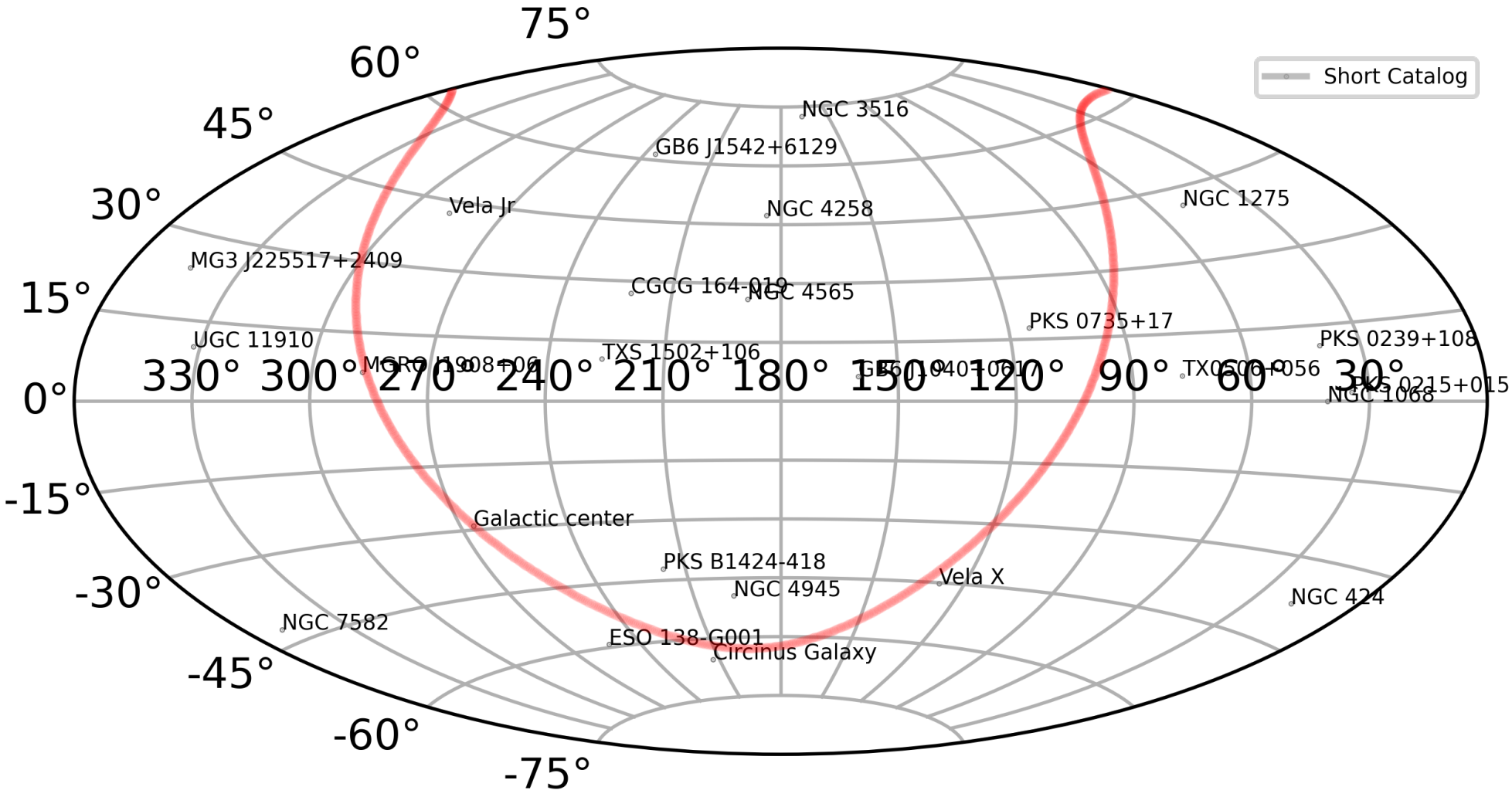
In order to track potential neutrino sources, 5 catalogs were formed during this work.

They include both well-known astrophysical objects, such as blazars and active galactic nuclei, and event catalogs published by Baikal-GVD, IceCube.

Created catalogs:

1. “Short” catalog of the potential neutrino sources
2. Published Baikal-GVD events
3. Alerts received from IceCube
4. “Extended” catalog including blazars, supernovae, active galactic nuclei

Short sources catalog



Work with databases

Both internal and incoming alerts should be available to the participants of the experiment at any time.

To ensure quick and convenient access, all alerts are stored in databases.

In the course of the work, scripts were created to connect to various types of databases, read the necessary information and visualize it.

Alerts coincidences

To notify the collaboration members, Baikal-GVD alert system sends e-mails with internal alerts as well as coincidences with incoming alerts

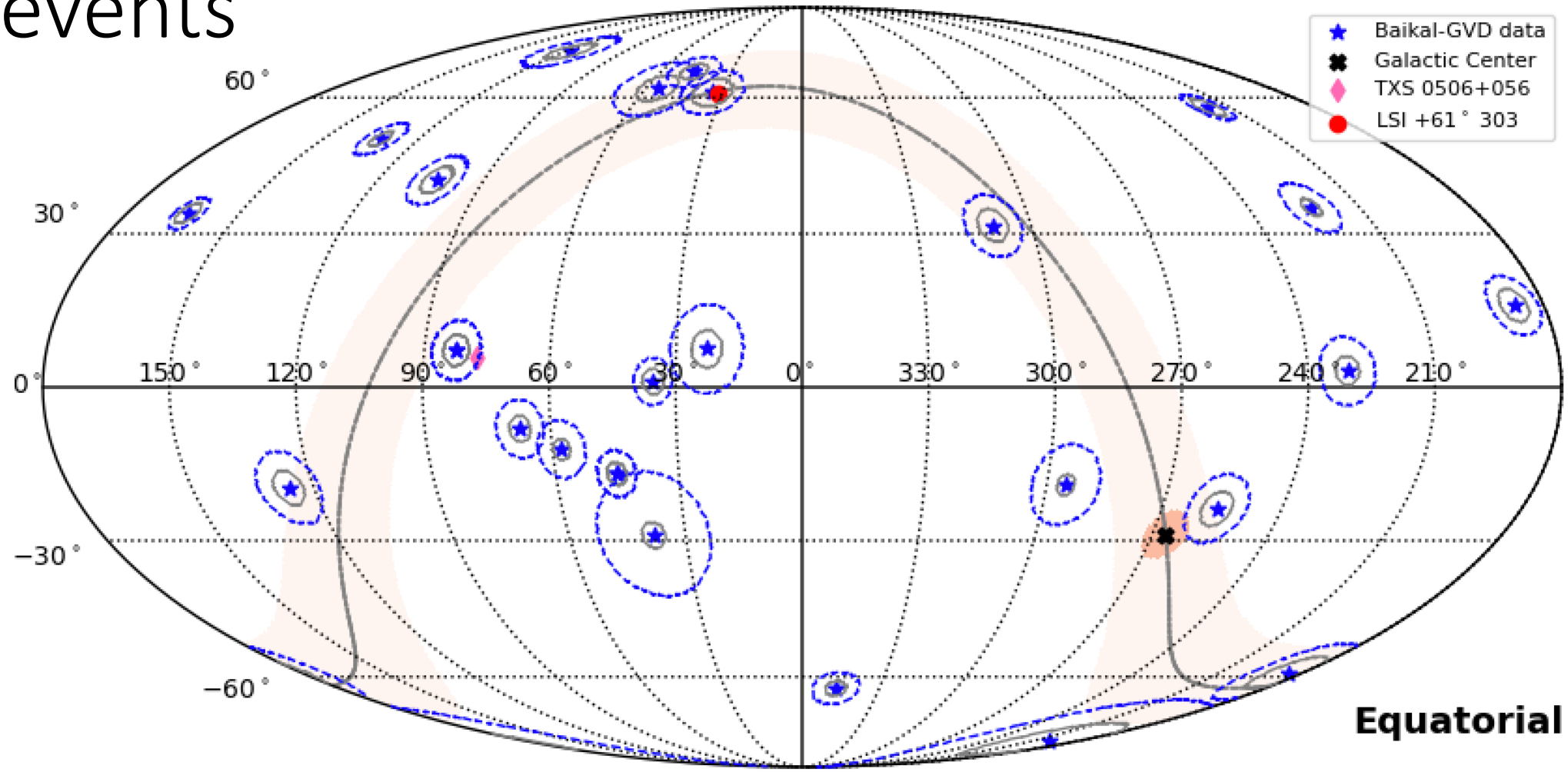
Baikal-GVD follows up different experiments. To find the potential coincedences with them, various approaches should be applied.

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

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Sat 14 Oct 23 22:00:53 UT
NOTICE_TYPE:      ICECUBE Astrotrack Bronze
STREAM:           25
RUN_NUM:          138449
EVENT_NUM:        20481611
SRC_RA:           296.0109d {+19h 44m 03s} (J2000),
                  296.3130d {+19h 45m 15s} (current),
                  295.3755d {+19h 41m 30s} (1950)
SRC_DEC:           +1.2386d {+01d 14' 19"} (J2000),
                   +1.2970d {+01d 17' 49"} (current),
                   +1.1179d {+01d 07' 04"} (1950)
SRC_ERROR:        34.43 [arcmin radius, stat-only, 90% containment]
SRC_ERROR50:      13.41 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE:   20231 TJD;   287 DOY;   23/10/14 (yy/mm/dd)
DISCOVERY_TIME:   79206 SOD {22:00:06.26} UT
REVISION:         0
ENERGY:           1.0532e+02 [TeV]
SIGNALNESS:       2.5416e-01 [dn]
FAR:              4.8518 [yr^-1]
SUN_POSTN:        199.68d {+13h 18m 44s}   -8.31d {-08d 18' 19"}
SUN_DIST:          96.75 [deg]   Sun_angle= -6.4 [hr] (East of Sun)
MOON_POSTN:       201.72d {+13h 26m 53s}   -8.85d {-08d 50' 47"}
MOON_DIST:         94.73 [deg]
GAL_COORDS:        40.13,-11.10 [deg] galactic lon,lat of the event
ECL_COORDS:       298.26, 22.16 [deg] ecliptic lon,lat of the event
COMMENTS:         IceCube Bronze event.
```

IceCube alert message

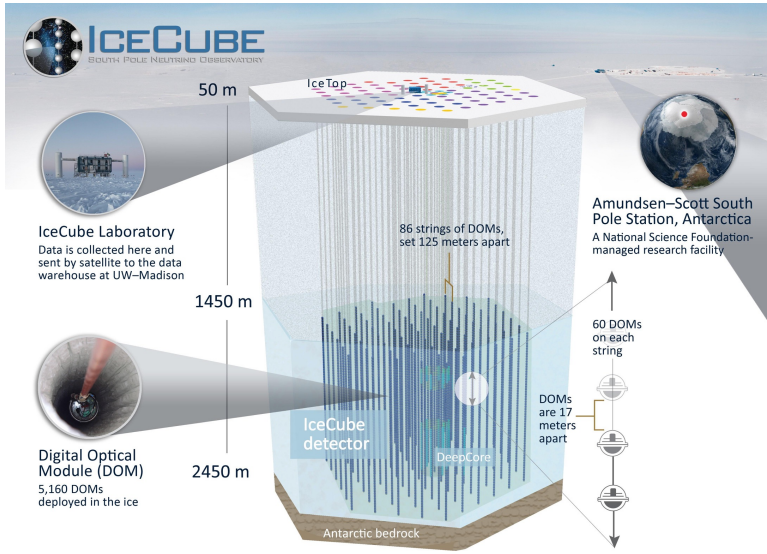
Published Baikal-GVD high-energy cascade events



Baikal-GVD Collaboration, V. A. Allakhverdyan et al. Physical Review D 107, 042005, (2023) and MNRAS, v.256, is.1, (2023)

Potential alerts coincidences with IceCube

Experiments to follow-up: IceCube

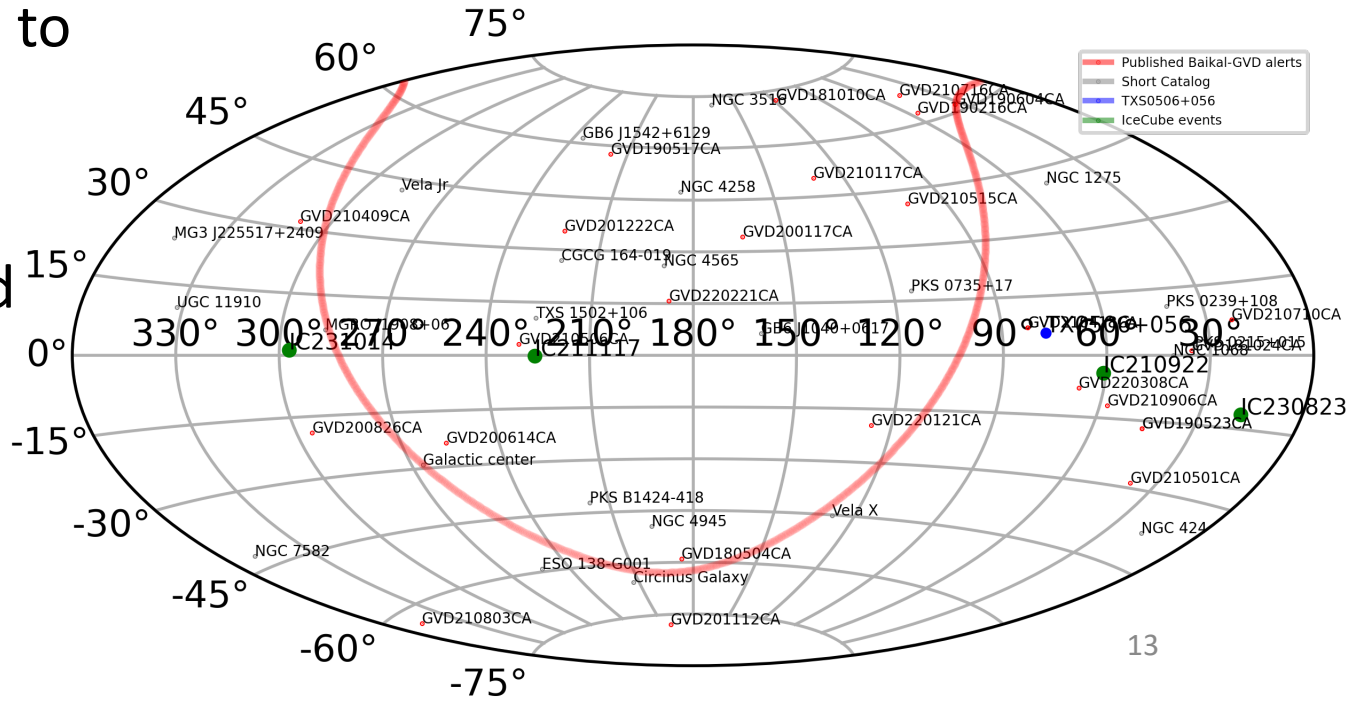


ON region: includes the IceCube 90% error and Baikal-GVD median angular resolution.

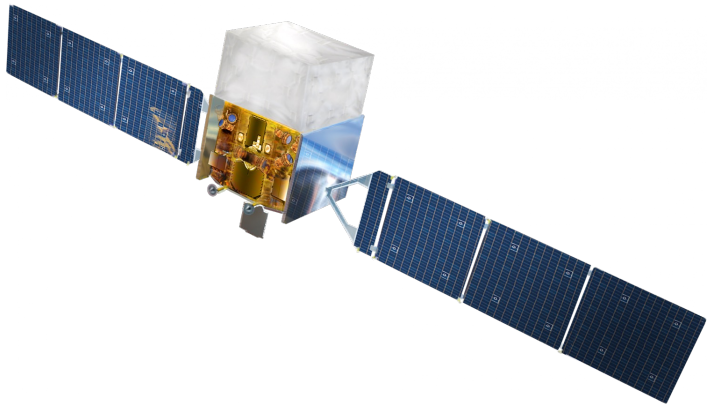
OFF region: the same size as ON region and centered on the alert position. Extended in RA coordinates and in time, then re-scaled to the size and time-span of the ON region.

Following time windows can be considered in alerts coincidences search process:

- [T0 – 1 h, T0 + 1 h]
- [T0 – 1 day, T0 + 1 day]



Potential alerts coincidences with GRB



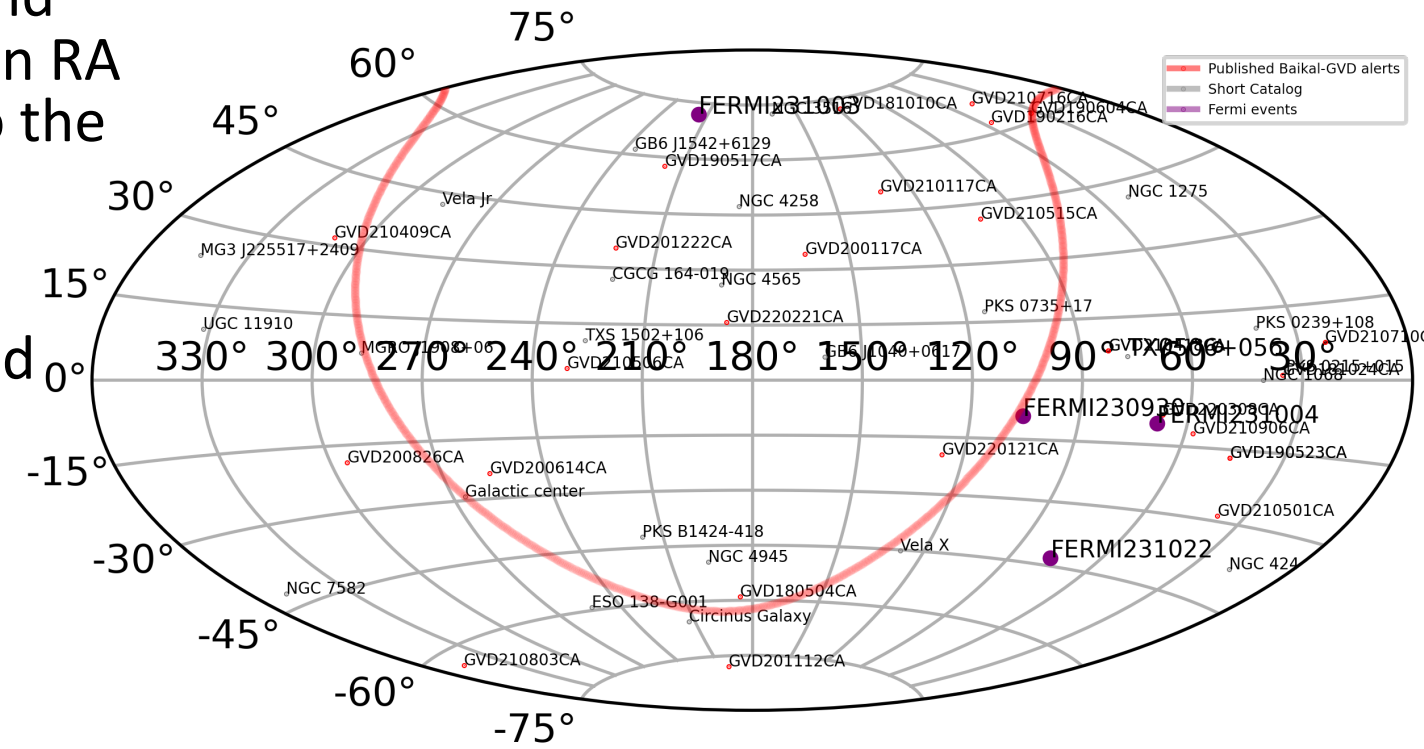
Experiments to follow-up: Fermi-GMB, Fermi-LAT

ON-region: the GRB error and Baikal-GVD median angular resolution

OFF-region: the same size as ON region and centered on the alert position. Extended in RA coordinates and in time, then re-scaled to the size and time-span of the ON region.

Following time windows can be considered (pre-burst and afterglow):

- [To - 1 day, To]
- [To – 1 day, To + 3 hours]
- [To – 1 day, To + 12 hours]
- [To – 1 day, To + 1 day]



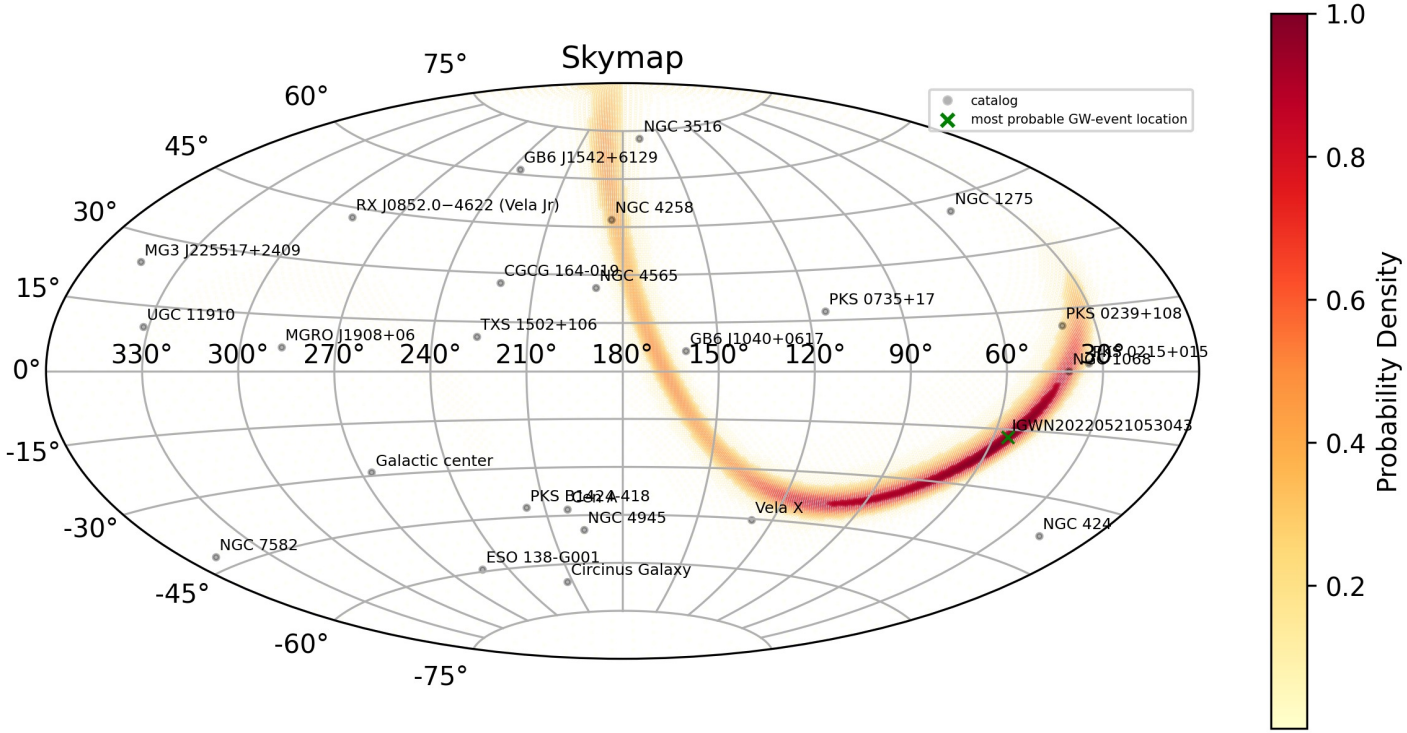
Potential alerts coincidences with LVK

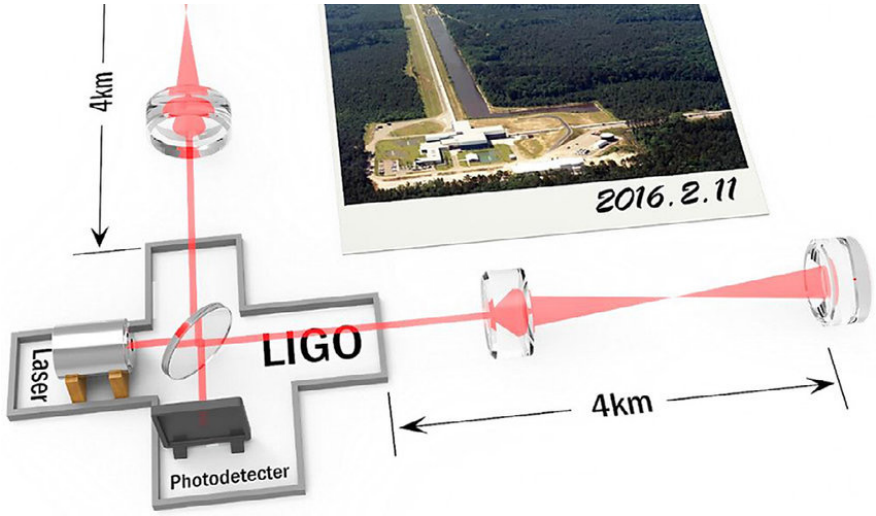
Experiments to follow-up:
Ligo/Virgo/Kagra gravitational wave (GW) obervatories

Types of incoming gravitational signals:
BBH, BNS, BHNS

For GW alerts following time windows can be considered (pre-burst and afterglow):

- [T_0 – 1000 s, T_0 + 1000 s]
- [T_0 – 1000s, T_0 + few days]





Plans

- Optimization of the alert visualization with Grafana (see A. Kulikov poster presentation)
- Optimization of the alerts storage in databases
- Automatization of the picture attachment in e-mails