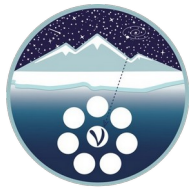
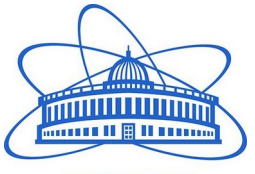
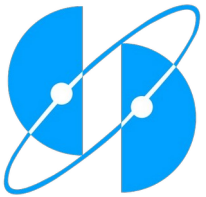




The Baikal-GVD telescope follow-up analysis of the IceCube neutrino alerts

V. Dik, A. Avrorin, Zh.-A. Dzhilkibaev, O. Suvorova, B. Shaibonov

on behalf of the Baikal-GVD collaboration

The 27th European Cosmic Ray Symposium 25.07.2022

BAIKAL-GVD

The purpose of the work

- Baikal-GVD has monitored online alerts from IceCube since August 2020.
- The goal of this work is the search for correlation in the direction and time of the signal in IceCube notifications with events reconstructed from Baikal-GVD data for muon and cascade modes.

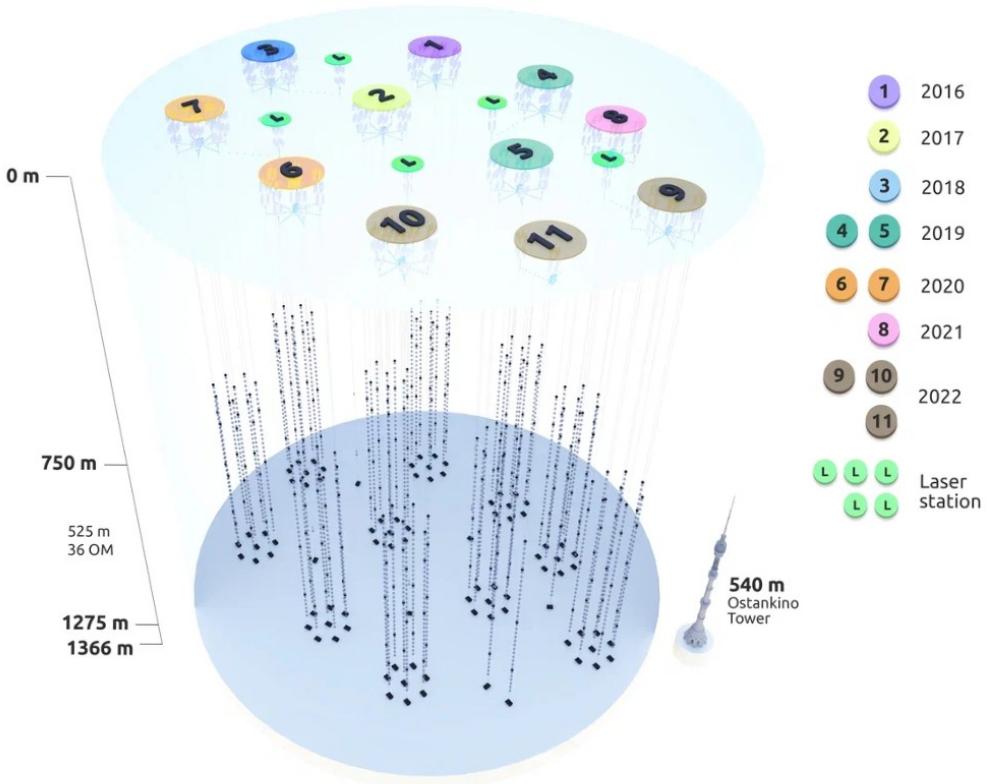
BAIKAL-GVD

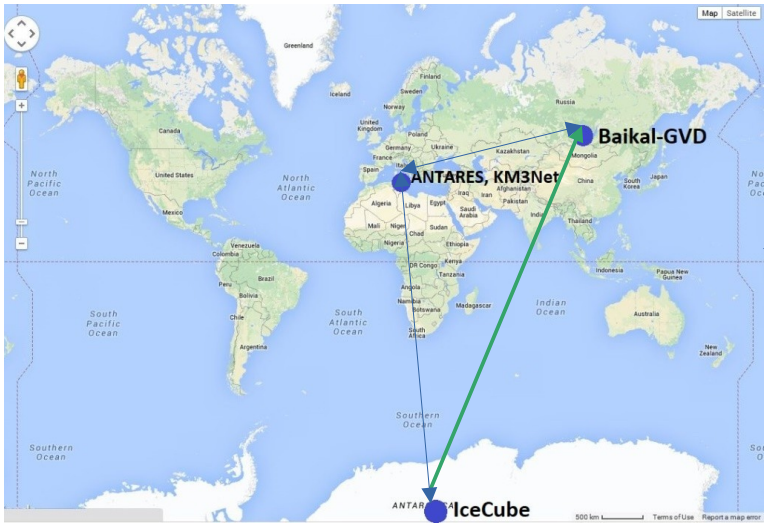
The content of the work

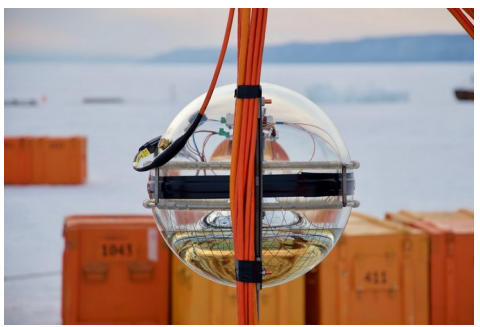
1. Baikal-GVD: general information.
2. The scheme of data transmission and processing in the follow-up regime.
3. The results of the search of correlations GVD-IC 2020-2022 by cascade mode.

Baikal Gigaton Volume Detector

In total for 2022: 10 clusters and 2916 optical modules with taking experimental strings into consideration



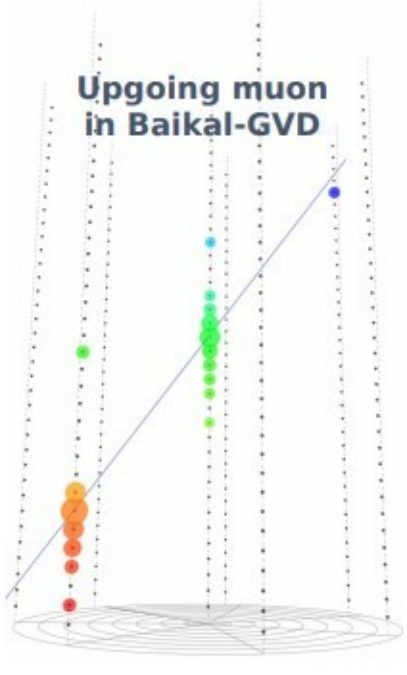


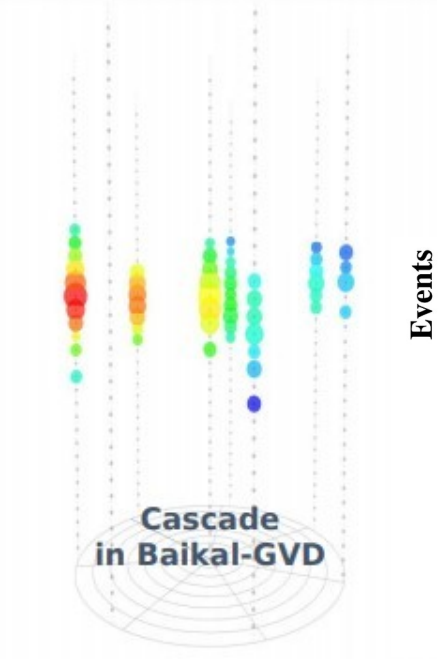


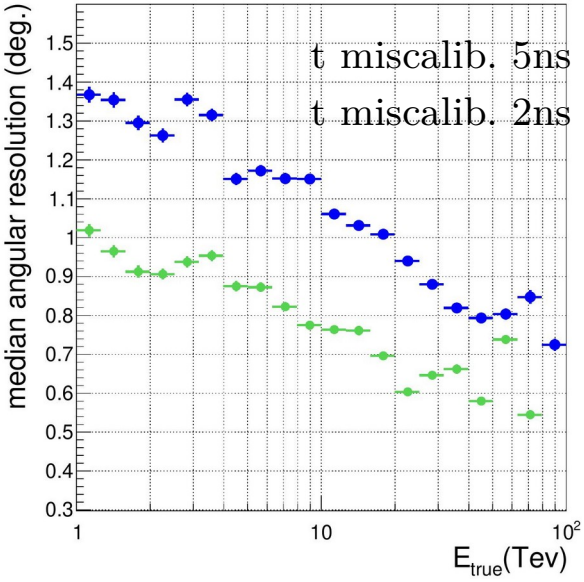
Muon track and cascade reconstruction modes

$$\nu_l + N^{CC} \rightarrow \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track + cascades \end{cases}$$

$$\nu_l + N^{NC} \rightarrow \nu_l + \text{cascade}$$

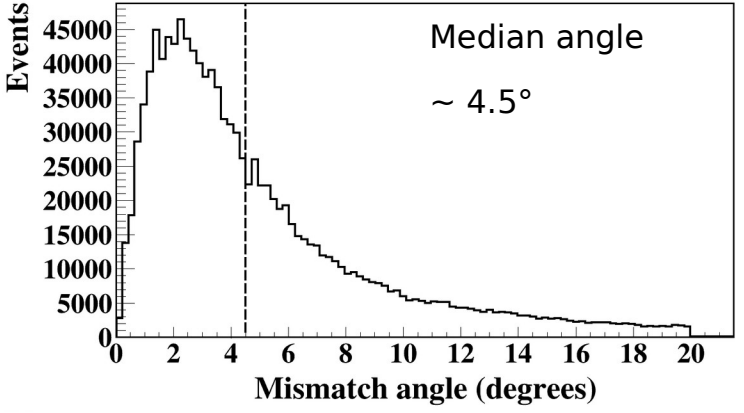






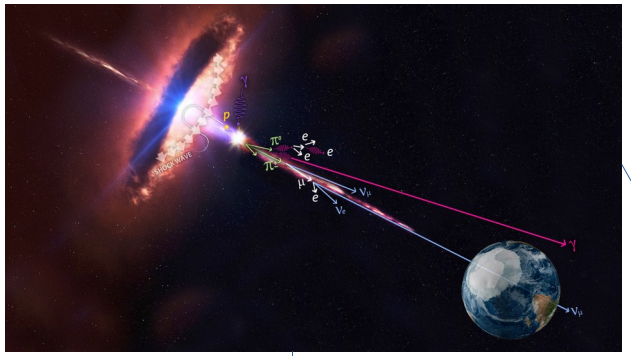
Median angular resolutions for single cluster track events, depending on the neutrino energy for two values of time accuracy.

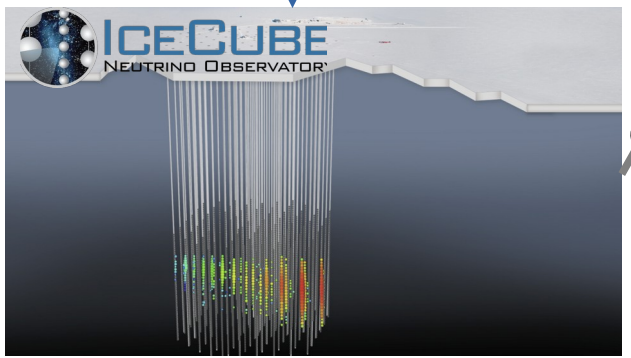
Online selection of track like events cuts off events with Zen<120º.



The distribution of cascade events by angle between simulated and reconstructed shower directions for single cluster.

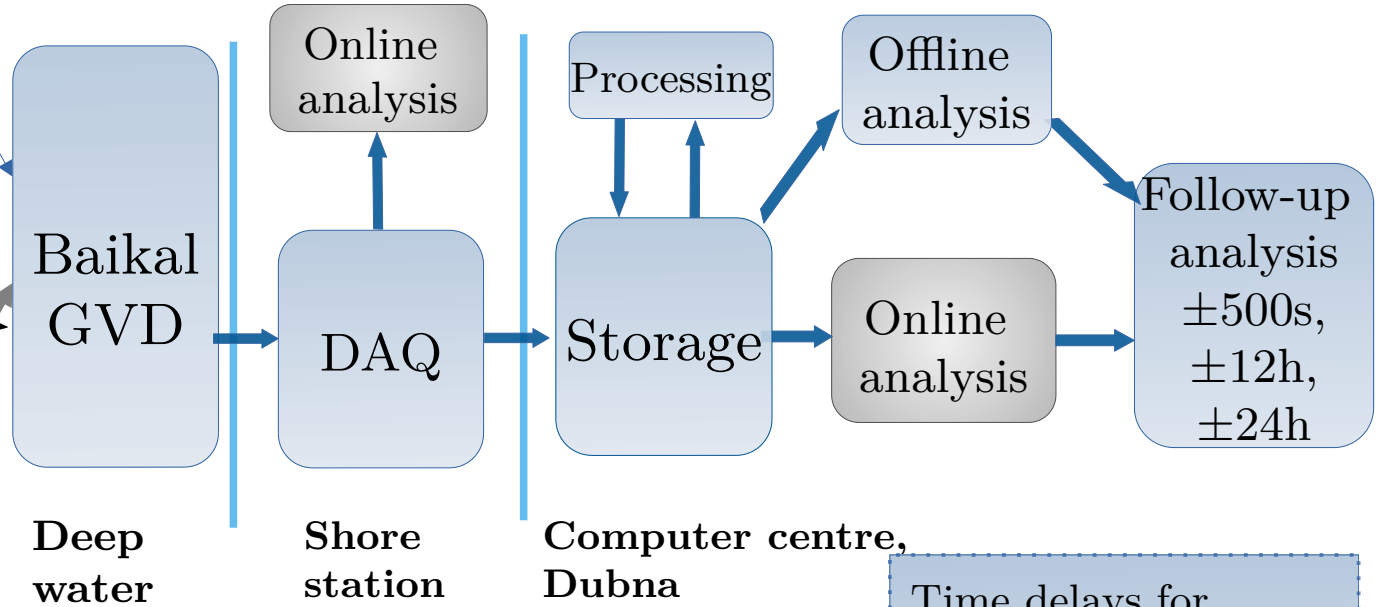
GVD work in follow-up regime





GCN

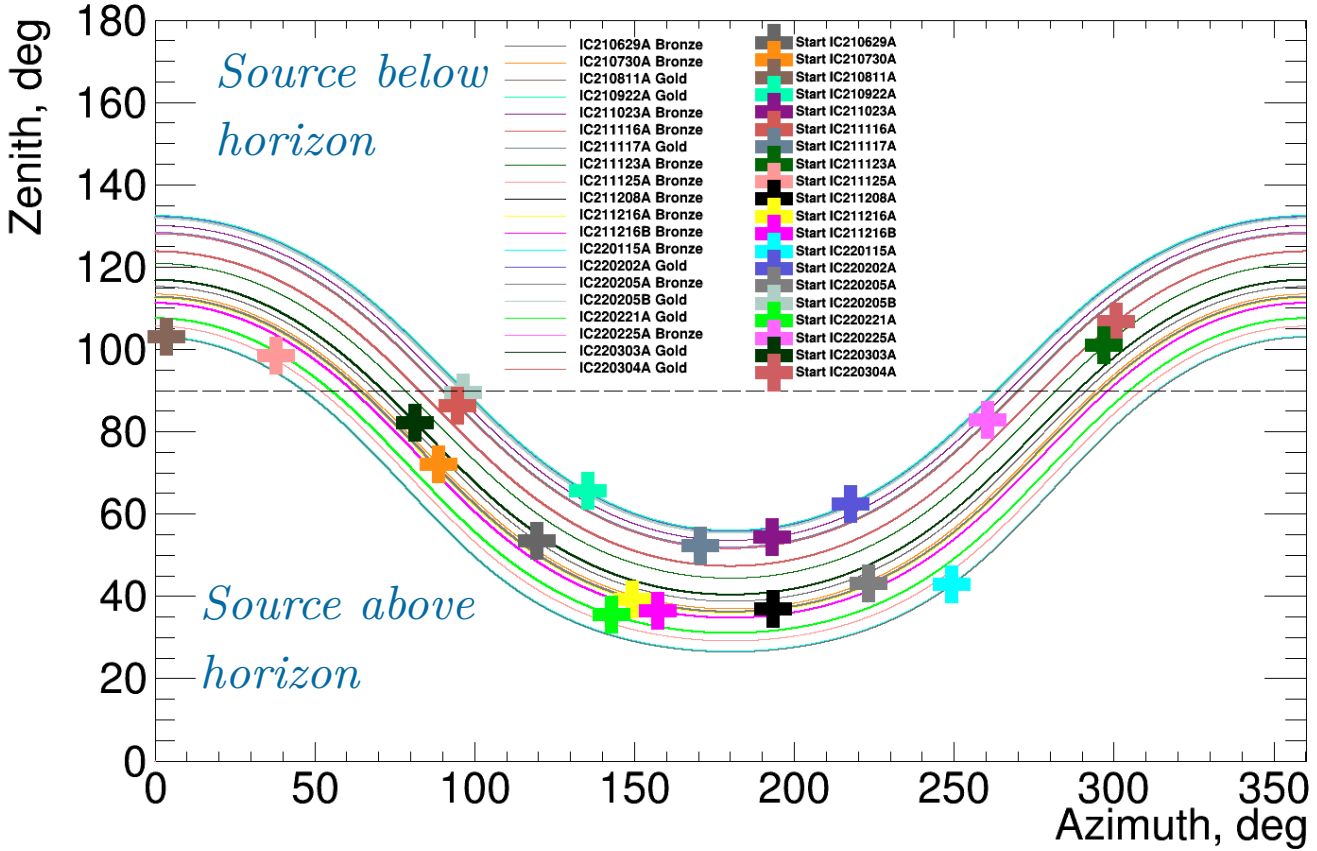
The scheme of data transmission and processing



Time delays for follow-up analysis:
Online ~ 3 min
Offline ~ 24 h

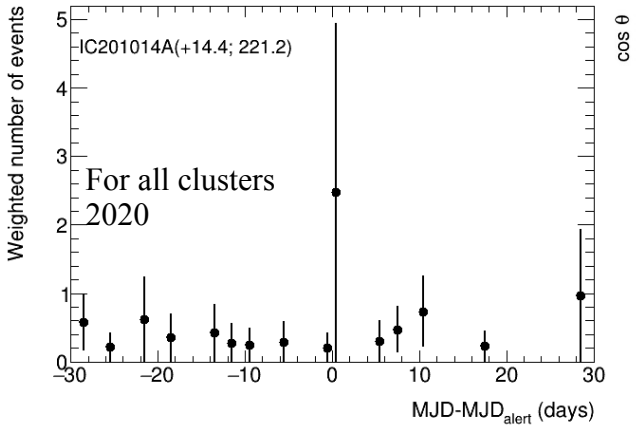
High energy IC events follow-up

Since 2020 year 57 IC alerts (notifications about signals) were tracked using GCN (**μ tracks ↑ E> 100 TeV**).

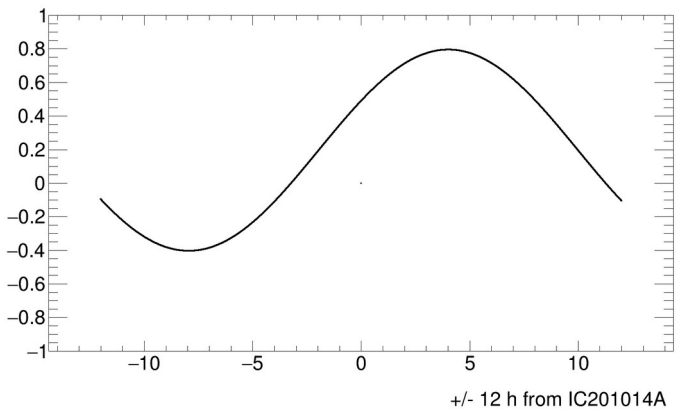


- Daily tracks of IC events 2021 in horizontal coordinates of Baikal-GVD.
- For the most of the IC alerts incoming directions are downgoing relative to the Baikal-GVD horizon, so Zen $< 90^{o}$.
- The search with GVD events is carried out in a cone: $\Psi=5^{o}$, 10^{o}.

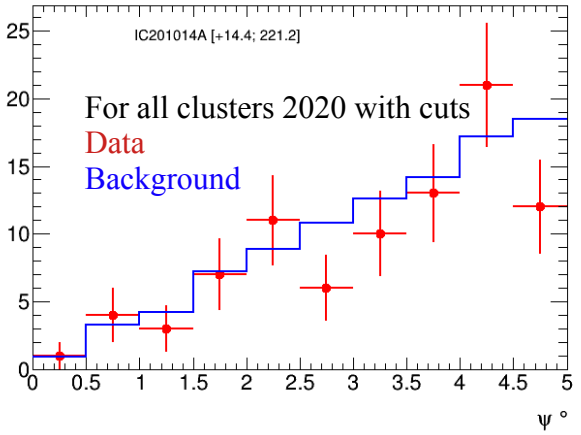
The example of the follow-up analysis for single cluster cascades and IC201014A



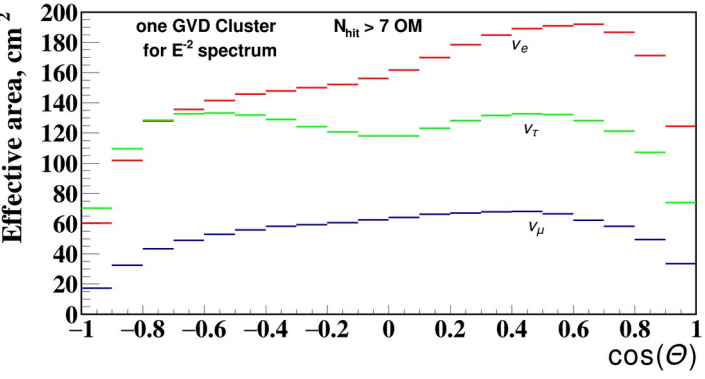
1. A number of GVD cascade events (weight =1/ψ) in ψ< 5º in ±30 days from the alert



2. Zenith angle in ± 12 h from alert's time



3. Background analysis: a number of cascade events, passing cuts in ψ<5º for 2020 year for alert's directon.



Effective area values for each neutrino flavour for E=1 TeV ÷10 PeV for single cluster.

4. A number of observing coincidences in ± 12 h: $\mathbf{N_{obs} = 1}$

A number of background events in ± 12 h: $\mathbf{N_{bg} = 0.44}$

P-value $= \mathbf{0.36}$

A limit on expected number of neutrino events: $\mathbf{n_{90\%}=4.36}$

Exposition (using Eff area): $\mathbf{Expos = 1787\ TeV^{-1}\ cm^2}$

A limit on the neutrino fluence:

$\mathbf{E^2F = n_{90\%}/Expos = 2.44 \cdot 10^{-3}\ TeV\ cm^{-2}}$

The results of follow-up analysis by single cluster cascade mode 2020-2021

1. **2020**: in the absence of significant excess above the background in ±12h upper limits on the neutrino fluence for spectrum E^{-2} were calculated: ~**1-2.5 GeV/cm²**.

2. **2021**: the next cut condition has been added to the coincidence algorithm for GVD cascade events: **E>40 TeV**.

3. **2021**: **5 coincidences** have been found with $E_{casc} > 40$TeV, **two** of them passed offline selection.

IC 211208A and PKS 0735+17 follow-up

- 08.12.2021 20:02: IceCube Bronze event E=171TeV in the vicinity of the bright blazar PKS 0735+17
- Active state of PKS 0735+17 was observed in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio
- **Baikal-GVD** downward-going **cascade-like event** E≈ 43 TeV **4 hr after** the IceCube event, **5.30°** from **IC211208A** and **4.68°** from **PKS 0735+17, Atel#15112** was sent
- Also BUST-211204A (Baksan) ~3σ (**Atel#15143**) and KM3Net 211215 ~1.1σ (**Atel#15290**)

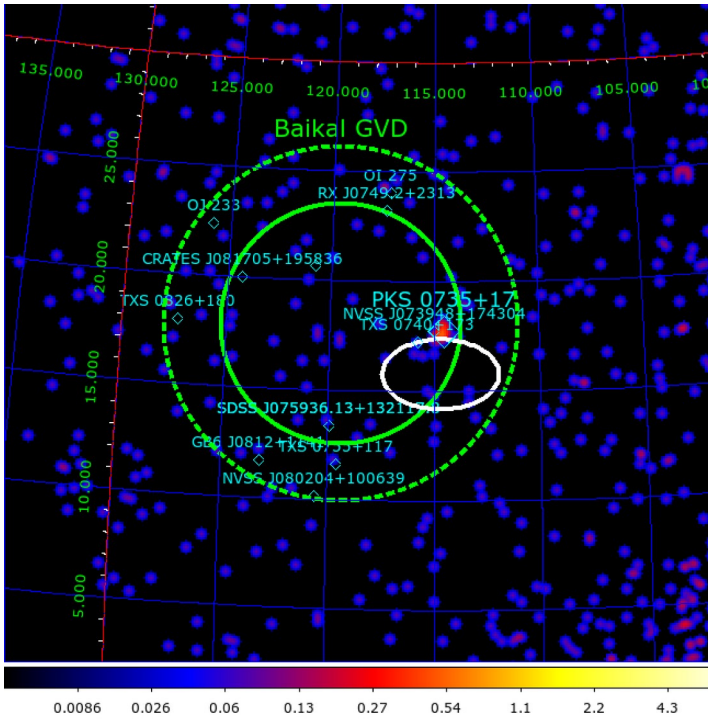
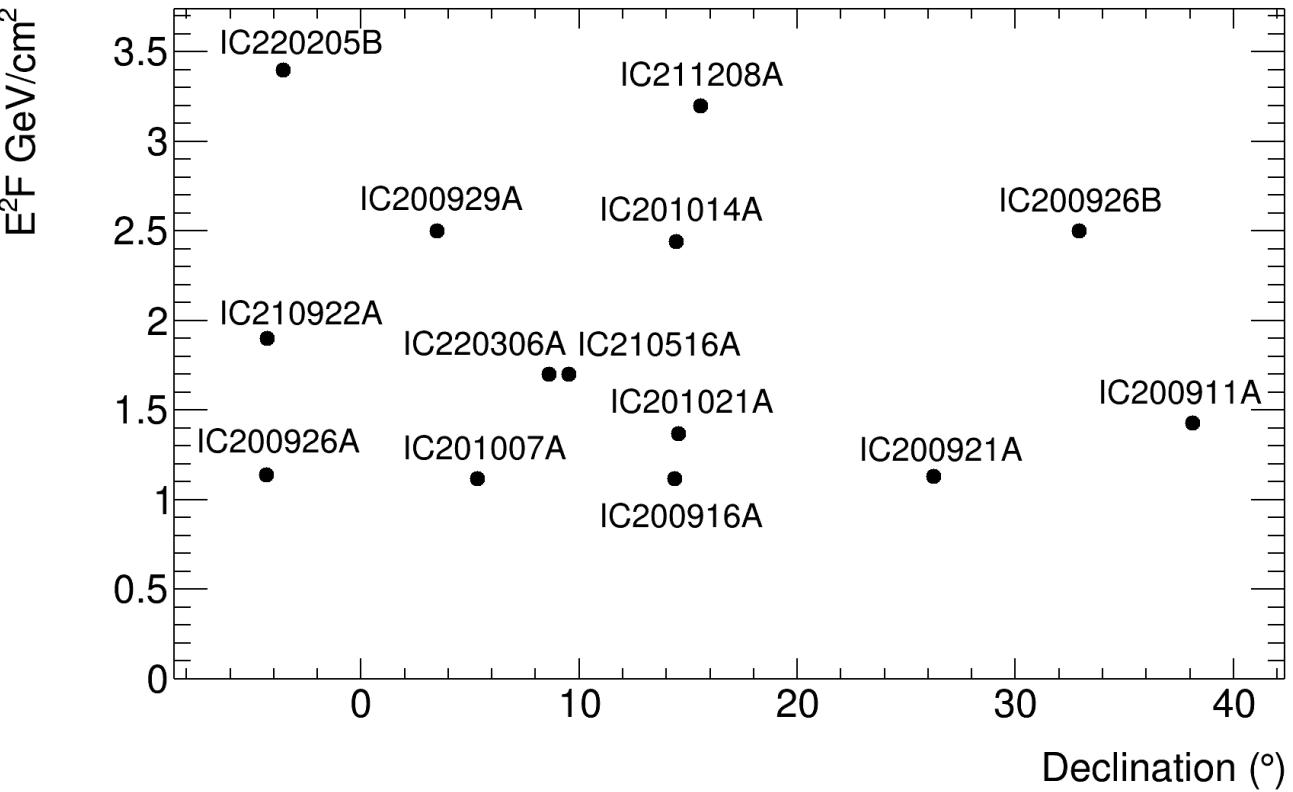


Image by D.Semikoz & A.Neronov

Pre-trial Baikal-GVD **p-value = 0.0044** (2.85 σ)
[24 hr, 5.5 deg cone]
Trial factor ~ 40

Also see N. Sahakyan et al., arXiv:2204.05060

Upper limits for neutrino fluence*, ** for IC 2020-2022



* For energies 1TeV – 10PeV with spectrum E^{-2} assuming equal fluence in all flavors.

The limit values **(2020 - 2021) were published:

- A.D. Avrorin et al., **High-Energy Neutrino Follow-up at the Baikal-GVD Neutrino Telescope**, Astron.Lett. 47 (2021) 2, 94-104, Astron.Zh. 47 (2021) 2, 114-124; DOI: 10.1134/S1063773721020018.
- V. Dik et al., **Follow-up of the IceCube alerts with the Baikal-GVD telescope**, JINST 16 (2021) 11, C11008; (VLVnT).
- O.V.Suvorova et al., **Multi-messenger and real-time astrophysics with the BaikalGVD telescope**, PoS ICRC2021 (2021) 946, (ICRC2021, VLVnT2021)
- O.V.Suvorova et al.,Neutrino 2022, Poster #0741

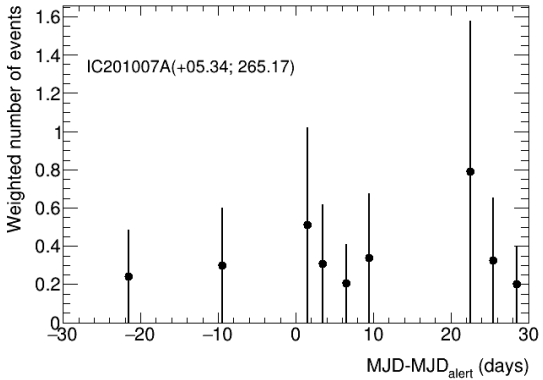
Conclusion

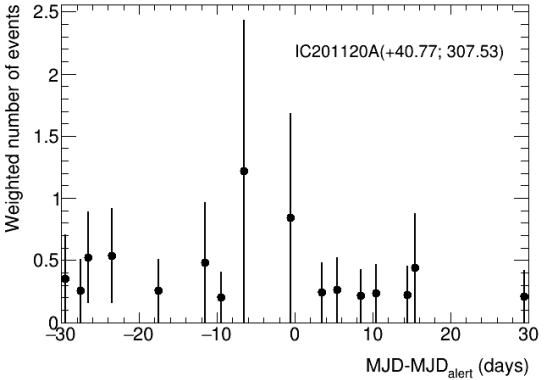
- Baikal-GVD tracks notifications about high-energy neutrino events IceCube in online regime.
- The results of the search of coincidences between track like events IceCube and cascade like events of Baikal-GVD for 2020-2022 were illustrated.
- For single cluster cascade mode the upper limits on the neutrino fluence at 90% C.L with E^{-2} spectrum and equal fluence in all flavors were calculated: **$1 \div 3$ GeV/cm^2**.

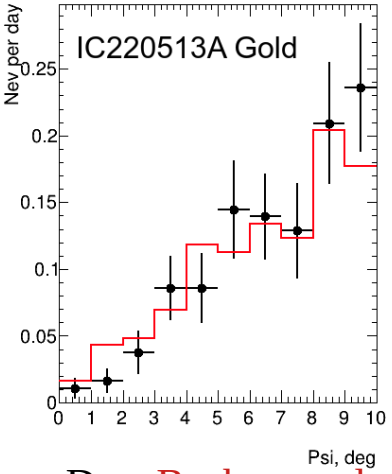
This work was supported by the Ministry of Science and High Education of the Russian Federation within the financing program of large scientific projects of the Science National Project (grant no. 075-15- 2020-778). The work of V. Dik was supported by grant of JINR for young scientists and specialists № 22-202-02.

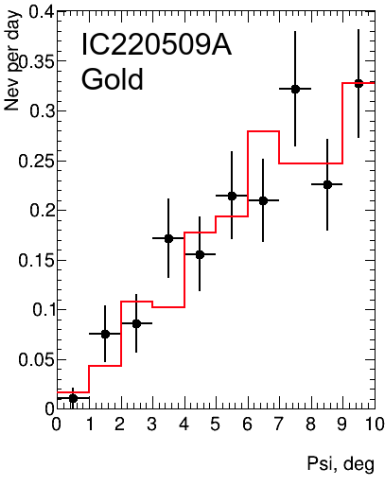
Thank you for attention!

Spatial-temporal and time analysis

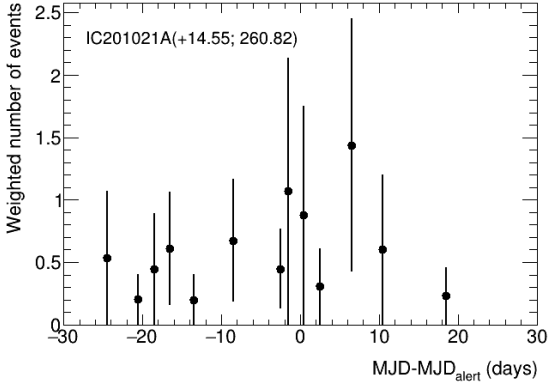


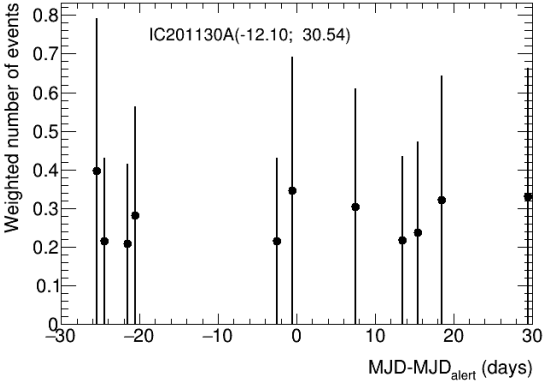


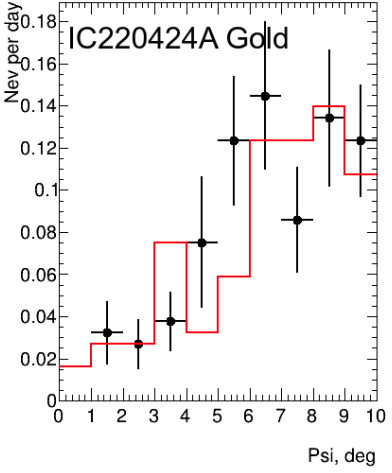


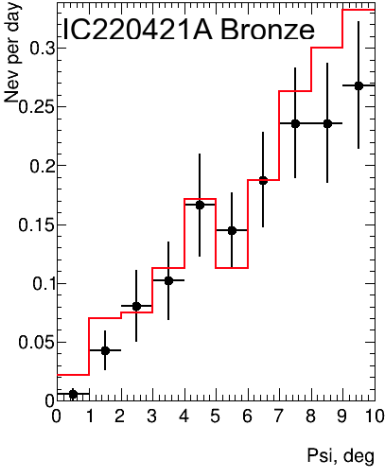


Data Background









Number of cascade events GVD (with weight $1/\psi$) $\psi < 5^{o}$ in ± 30 d from alert time

Number of cascade events GVD in $\psi < 10^{o}$ for 2021 in alert direction

Equations

$$1 - C.L. = e^{-s_{up}} \frac{\sum_{m=1}^{n} (s_{up} + b)^m / m!}{\sum_{m=1}^{n} b^m / m!}$$

$$\Phi_{\nu}^{up} = \frac{s_{up}}{\overline{S}_{eff} \cdot T}$$

$$\overline{S}_{eff} = \frac{\int S_{eff}(E) \cdot \Phi_{\nu}(E) dE}{\Phi_{\nu}(E)}$$

1. Upper limit S_{up} (Bayes method) is calculated by numerical method of equation's solution

2. Φ – upper limits