Annex 3.

Form of opening (renewal) for Project /
Sub-project of LRIP

APPROVED

JINR DIRECTOR

____________/_____________________

"_____"_________________ 2023

SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING / RENEWAL OF PROJECT/SUB-PROJECT OF LARGE RESEARCH INFRASTRUCTURE PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the project/subproject of the large research infrastructure project (hereinafter LRIP)

1.1 Theme code / LRIP (for renewable themes) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*
03-2-1100-2010/2024

1.2 Project/sub-project of a MIP code (for renewed themes)

1.3 Laboratory
Dzhelepov Laboratory of Nuclear Problem

1.4 Scientific field
Major infrastructure project, Nuclear physics

1.5 The name of the Project/subproject of the LRIP
BAIKAL-GVD, Deep underwater muon and neutrino detector on Lake Baikal (Gigaton Volume Detector)

1.6 Project/ sub-project of the LRIP Leader(s)
Igor Belolaptikov

1.7 Project/sub-project of the LRIP Deputy Leader(s) (scientific supervisor of the project/sub-project of the LRIP)

2 Scientific rationale and organisational structure

2.1 Annotation

Baikal-GVD project is further development of gigaton volume neutrino telescope for research in the field of multichannel astronomy, study of the fundamental properties of the most energetic cosmic neutrinos, indirect search for galactic “dark” matter and applied research. The Baikal-GVD Collaboration is constructing a neutrino telescope in Lake Baikal. Arrays of light-sensitive elements record the Čerenkov light produced by fast travelling charged particles in the lake water, these particles could originate from interactions of neutrinos. The energy and direction of the original neutrinos reconstructed from the amount of Čerenkov photons and their time-of-arrival in the detector. The telescope is measuring cosmic neutrinos and searching for their sources as well as possible neutrino flux from Dark Matter annihilation and other rare phenomena. The scientific program of the project will be focused on fundamental problems of astrophysics and elementary particle physics: identification of astrophysical sources of ultrahigh-energy neutrinos, mechanisms of formation and evolution of galaxies, determination of the neutrino mass hierarchy, neutrino geophysics, etc. The unique neutrino telescope Baikal-GVD is one from the main JINR basic facilities. During the next 5 years extensive development of the telescope and its infrastructure at JINR and on the lake Baikal will be continued.

2.2 Scientific justification (purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks)

Purpose:

The presented BAIKAL-GVD Project in the Lake Baikal represents further development of efforts over the past decades by the BAIKAL Collaboration on the previous phases. The optical properties of the deep-water lake now have been well understood, and the detection of high-energy neutrinos has been successfully demonstrated. These achievements are the base for the Gigaton Volume Detector (BAIKAL-GVD), with superior detector performance and an effective telescope size at or above the kilometer-scale.

Presently developing stage of the BAIKAL-GVD with new research infrastructure aims primarily at studying astrophysical neutrino fluxes, in particular, mapping the high-energy neutrino sky in the Southern Hemisphere including the region of the galactic center. Other topics include indirect search for dark matter by detecting neutrinos produced in WIMP annihilation in the Sun or in the center of the Earth. BAIKAL-GVD will also search for exotic particles like magnetic monopoles, super-symmetric Q-balls or nuclearites.

Specific Project Objectives are:

Neutrinos from local astrophysical objects

The natural high-energy neutrino fluxes are produced by physical processes in astrophysical objects characterized by enormous energy release at rates from 10^{39} to 10^{52} erg/s or higher. The nearest (with respect to a terrestrial observer) astrophysical objects that are currently assumed to be capable of emitting high-intensity neutrino fluxes are located mainly in the vicinity of the Galactic center and in the Galactic plane. Supernova remnants, pulsars, the neighborhood of the black hole at the Galactic center, binary systems containing a black hole or a neutron star, and clusters of molecular clouds that are targets for cosmic-ray protons and nuclei are the most promising Galactic sources with respect to the detection of their neutrino emission. The energy spectrum of neutrinos from Galactic sources is in the energy range $10^3 \div 10^6$ GeV.

Extragalactic objects — active galactic nuclei (AGN), gamma-ray bursts (GRB), starburst galaxies and galaxy clusters — belong to another class of neutrino sources whose emission can be recorded by ground-based facilities. This class of sources is characterized by much greater energy release and generates neutrinos in the energy range $10^4 \div 10^8$ GeV or higher. Searching for a neutrino signal from identified sources imposes stringent requirements on the resolution of neutrino telescopes from the viewpoint of measuring both neutrino energy and direction.

Diffuse neutrino flux

The other direction of research on the astrophysical neutrinos is to investigate the energy spectrum, global anisotropy, and neutrino flavor composition of the diffuse neutrino flux from unidentified sources at energies above 10^4 GeV, at which the background from atmospheric neutrinos is comparable to or lower than the expected flux. The diffuse high energy neutrino flux near the Earth is produced by neutrino emission from the entire set of sources during the period from remote cosmological epochs to the present day. Extragalactic sources make a major contribution to this flux. The neutrinos produced by the interaction of cosmic rays with interstellar matter and, in the case of ultra-high-energy cosmic rays, with electromagnetic radiation from a wide energy range, including the cosmic microwave background, also contribute to the diffuse flux. It should be noted that the neutrinos from the decay of supermassive particles associated, in particular, with Grand Unified Theories (GUT) (top-down scenario) could account for a certain fraction of the diffuse flux.

Dark matter

One of the challenges of modern natural science is to find Dark Matter (DM) particles. Observational data in the field of astronomy and cosmology suggests that, apart from ordinary matter, there is matter of a new type - DM - in galaxies, galaxy clusters, and the Universe as a whole. Moreover, on the whole, the DM matter in the Universe exceeds that of ordinary matter by a factor of 5-6.

To all appearances, the DM is composed of as yet unknown particles with the masses which exceed appreciably that of the heaviest known stable elementary particle - the proton. These new particles must have a lifetime comparable to or exceeding the age of the Universe. Undoubtedly, such a long lifetime is related to new conservation laws in fundamental physics. It can be said with great confidence that a whole stratum of new phenomena in particle physics occurring at ultra-high energies and inaccessible to investigation on existing accelerators stands behind the DM particles.

DM particles would interact very weakly with ordinary matter. Therefore, their direct detection, if at all possible, is an extremely complicated problem of experimental physics. An indirect approach to detect DM particles associated with the search for the products of their annihilation at the center of the Earth, the Sun, or the Galaxy is also very promising. There must be neutrinos of fairly high energies among these products, which, in turn, interact very weakly with matter and pass through the Earth or the Sun virtually without absorption. Neutrinos of such energies are successfully recorded on large underground facilities and neutrino telescopes placed in natural media.

The methods of searching for dark matter particles with underground detectors and neutrino telescopes in natural media consist in recording an excess of the muon flux in a direction away from the center of the Earth or the Sun or from the Galactic center above the background from atmospheric neutrinos. The constraints on the additional muon flux in a direction away from the Earth’s center and the Sun have been obtained on the Baksan, Super-Kamiokande, and MACRO underground facilities as well as on the underwater and under-ice neutrino telescopes NT200 (Lake Baikal), ANTARES (Mediterranean Sea), AMANDA and IceCube (South Pole). Underground neutrino detectors have a lower muon detection energy threshold ($\sim 1 \div 3$ GeV) than deep underwater (under-ice) facilities. Therefore, these two classes of detectors complement each other. The former are efficient at searching for particles with a mass below 80 GeV (the threshold W-boson production energy), while the latter are efficient at investigating particles with a mass of about 100 GeV or higher.

A further substantial increase in the sensitivity of an experiment to the muon flux from the annihilation of dark matter particles can be achieved only by increasing their effective area. In the case of neutrino telescopes, the problem is reduced to creating cubic-kilometer facilities. In the case of underground facilities, such an increase in the effective area implies an increase in the characteristic detector sizes to a hundred meters or more. Creating such a huge underground facility seems extremely unrealistic at present.

Atmospheric neutrinos

Cosmic rays generate the most intense neutrino flux observed in ground-based experiments in the energy range from hundreds of MeV to hundreds of TeV. A large number of pions and kaons are produced when cosmic rays interact with atmospheric matter. The pion, kaon, and muon decay reactions

$$\pi^{\pm} \to \mu + \nu_{\mu};\;\; K^{\pm} \to \mu + \nu_{\mu};\;\; \mu \to e + \nu_{\mu} + \bar{\nu}_e$$

produce the neutrinos which are referred to as *conventional* atmospheric neutrinos. In the energy range 100 GeV÷100 TeV, the spectrum of *conventional* atmospheric neutrinos is described by the expression:

$$\frac{d^2N}{dE_\nu d\Omega}(E_\nu,\theta) = A_\nu (E_\nu/\text{ГэВ})^{-\gamma}\left[\frac{1}{1+6E_\nu/E_\pi(\theta)} + \frac{0.213}{1+1.44E_\nu/E_K(\theta)}\right],$$

where A_ν = 0.0285 GeV^{-1} cm^{-2} s^{-1} ster^{-1}, γ = 2.69, E_π and E_K are the critical energies of the pions and kaons (the energies at which the decay probability is equal to the interaction probability) dependent on the zenith angle θ.

The primary cosmic rays are distributed isotropically near the Earth, but the development of cascades initiated by primary radiation in the atmosphere breaks the isotropy of the fluxes of secondary particles. The pions and kaons produced by a primary particle at large zenith angles spend much of their time in a rarefied atmosphere, where the decay probability is higher than the interaction probability. Therefore, the horizontal neutrino flux exceeds the vertical one. As the energy grows, the lifetime of pions and kaons increases and, accordingly, the decay probability decreases compared to the interaction probability. Therefore, the energy spectrum of the neutrinos produced by pions and kaons becomes steeper with growing energy (the exponent γ increases by one) than the primary cosmic- ray spectrum. The uncertainty in the predictions of the neutrino fluxes from pions and kaons is related to the uncertainty in the cosmic-ray flux and energy spectrum as well as to the uncertainty in the fraction of the kaons and pions produced in a nuclear interaction at high energies. The difference in the spectra of atmospheric neutrinos from pions and kaons calculated by different authors is about 25%.

A different neutrino production mechanism is possible at energies above 100 TeV. The *prompt* neutrinos can be produced in the decays of charmed mesons and baryons with a lifetime of the order of or less than 10^{-12} s. The spectrum of prompt neutrinos essentially follows the cosmic-ray spectrum and is flatter than that of conventional neutrinos. No prompt neutrinos have been experimentally detected so far. According to calculations, the energy at which the fluxes of prompt neutrinos become equal to and then exceed the conventional neutrino fluxes depends on the model for the interaction of primary cosmic rays with the air nuclei and on the zenith angle. For the vertical neutrino flux, this energy lies within the range 100-1000 TeV and increases with zenith angle.

From the viewpoint of experiments on neutrino telescopes, atmospheric neutrinos are the source of the natural irreducible background that complicates significantly the detection of astrophysical neutrinos. On the other hand, since the theoretical prediction level of the intensity and characteristics of the atmospheric neutrino flux is fairly high, this flux can be effectively used as a calibration neutrino flux. In addition, searching for prompt neutrinos is an important scientific task.

Magnetic monopoles

The concept of a magnetic monopole was introduced into the modern physical theory in 1931 by Dirac. He showed that any magnetic charge should be a multiple of the minimum possible charge g uniquely related to the minimum electric charge:

$$g = (\hbar c/2e) \approx (137/2e).$$

Thus, the minimum magnetic charge is approximately a factor of 68.5 larger than the minimum electric charge. In particular, this implies that the ionization energy losses for relativistic monopoles in a medium are much larger than those for relativistic muons. This opens good possibilities for the detection of fast monopoles in experiments with neutrino telescopes. The theory of Čerenkov radiation from magnetic monopoles was first examined by I.M. Frank [Vavilov-Čerenkov radiation. Russian. Moscow: Nauka, 1988, p. 192.]. The linear density of Čerenkov radiation with a wavelength A (under the assumption that the permeability of the medium is $\mu \sim 1$) is described by the expression:

$$\frac{d^2 n_c}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(\frac{ng}{e}\right)^2\left(1 - \frac{1}{n^2\beta^2}\right),$$

where g is the magnetic charge of the monopole, e is the charge of electron, n is the refractive index of the medium (for water, $n = 1.33$), $\beta = v/c$ is a monopole velocity expressed in units of the speed of light in vacuum and α is the fine-structure constant.

The Čerenkov radiation from a relativistic monopole in water is a factor of $(ng/e)^2 \approx 8300$ more intense than that from a relativistic muon. Thus, a magnetic monopole with a speed $\beta \sim 1$ is a bright light source corresponding in intensity to a muon with an energy of $\sim 1.4 \times 10^4$ TeV.

As a result of its acceleration in Galactic magnetic fields, the kinetic energy of a heavy monopole can reach $\sim 10^{11}$ GeV. On the other hand, when passing through the Earth, the energy losses of quasi-relativistic monopoles with $\beta > \beta_c$ ($\beta_c = 0.75$ is the threshold speed of the monopole with respect to the generation of Cherenkov radiation) are $\sim 10^{11}$ GeV. It thus follows that monopoles with a mass of less than 10^{11} GeV passing through the Earth remain quasi-relativistic and can be detected by their Čerenkov radiation with neutrino telescopes.

In 1981, V. Rubakov [JETP Lett. 33 (1981), p. 644.] published a paper where he concluded that the processes with baryon number nonconservation are not suppressed in the presence of a monopole predicted by GUT. The cross section for the reaction of monopole catalysis of baryon decay was estimated as:

$$\sigma_{\text{cat}} = \sigma_0 \beta_{\text{mon}}^{-1},$$

where a_0 was taken to be equal in order of magnitude to the characteristic values of strong interactions: $a_0 \sim 10^{-28}$ cm^2. When the electromagnetic interaction between a monopole and a nucleus incorporating a nucleon is taken into account, the factors $F(\beta_{mon}) = 2.4 \cdot 10^7 \beta_{\text{mon}}^{3.1}$ for the nucleons constituting the ^{16}O nucleus and $F(\beta_{\text{mon}}) = 0.17 \cdot \beta_{\text{mon}}^{-1}$ for free protons appear in the expression for the catalysis cross section. A monopole moving in water with a speed less than or of the order of 10^{-3} of speed of light must initiate mainly the decay of hydrogen nuclei with the cross section

$$\sigma_{\text{cat}}^{p} = 0.17 \sigma_0 \beta_{\text{mon}}^{-2}.$$

The energy being released in a single catalysis event ($m_p c^2 = 938$ MeV) is distributed between the proton decay products. While propagating in water, the latter become the sources of Čerenkov radiation, which is also generated by their daughter particles, δ-electrons, e^+e^- pairs, etc. As a result of each proton decay, up to $N_\gamma = 1.1 \cdot 10^5$ Čerenkov photons are emitted in the wavelength range $300 < \lambda < 600$

nm. Thus, the trajectory of the muon inducing proton decays when crossing a water volume must appear as a chain of flashes with a Čerenkov spectrum.

Neutrino Interactions

Natural high-energy neutrinos interact with the target material of neutrino telescopes mainly through the reactions on nucleons via the channels of charged (CC) and neutral (NC) currents:

$$\nu_l(\bar{\nu}_l) + N \overset{\text{CC}}{\to} l^-(l^+) + \text{hadrons}, \qquad (3.1)$$

$$\nu_l(\bar{\nu}_l) + N \overset{\text{NC}}{\to} \nu_l(\bar{\nu}_l) + \text{hadrons}, \qquad (3.2)$$

$$\bar{\nu}_e + e^- \to W^- \to \text{anything}, \qquad (3.3)$$

where $l = e, n$ or τ. The interaction of neutrinos with target electrons makes virtually no contribution to the total number of recorded events, except for the resonant scattering of electron antineutrinos in the W-resonance region, with the energy at resonance $E_0 = M_W^2/2m_e = 6.3 \times 10^6$ GeV and a cross section of 5.02 x 10^{-31} cm^2. The final products of reactions (3.1)-(3.3) — leptons and high-energy cascades — carry information about the energy, direction, and, in principle, flavor of neutrinos.

In experiments on deep underwater and under-ice Čerenkov detectors, the effective target size depends on the neutrino energy and flavor. In the case of muon neutrinos, both the transparent medium around the telescope and the bedrock are the neutrino target, because the secondary muons have a high penetrating power. In the former case, the muon neutrino energy can be determined by reconstructing the energies of the muon and the shower generated at the neutrino interaction vertex. During a muon neutrino interaction in rock, the neutrino energy in each individual event cannot be reconstructed exactly due to the energy losses of the muon as it propagates from the interaction vertex to the facility. However, when the statistics of recorded events is large enough, the energy spectrum of the muon neutrino flux can be derived by the reconstruction of the muon energy. The astrophysical fluxes of ν_e and ν_τ, which account for two thirds of the total flux, can be investigated in experiments on neutrino telescopes only by recording the secondary showers generated in a water target. Hadronic showers are produced in the interactions of neutrinos of all flavors with nuclei via the channels of charged and neutral currents. In addition, in the case of the CC interaction of electron and τ-neutrinos, the electron energy is converted into the energy of an electromagnetic shower, while a significant fraction of the τ-lepton energy is transferred to the hadronic or electromagnetic shower as a result of its decay. Thus, achieving a high accuracy of reconstructing the energy and direction of showers is an indispensable requirement for efficient detection of neutrinos of all flavors.

Methods and approaches, Methodologies:

The detector will utilize Lake Baikal water instrumented at depth with optical sensors that detect the Čerenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented volume. The concept of BAIKAL-GVD is based on a number of evident requirements to the design and architecture of the recording system of the optical sensors array: the utmost use of the advantages of array deployment from the ice cover of Lake Baikal, the extendibility of the facility and provision of its effective operation demonstrated during so far performed stages of the deployment, and the possibility of implementing different versions of arrangement and spatial distribution of light sensors within the same measuring system.

The BAIKAL-GVD site is located in the southern basin of Lake Baikal. It has been selected from unique combination of hydrological, hydrophysical, and landscape factors which are optimal for deployment and operation of the neutrino telescope. Lake depth is about 1360 m here at distances beginning from about of three kilometers from the shore. The flat lake bed throughout several tens of kilometers from the shore allows practically unlimited instrumented water volume for deep underwater detector. A strong up to 1 m thick ice cover from February to the middle of April allows telescope deployment (fig. 3), as well as maintenance and research works directly from the ice surface, using it like a solid and fixed assembling platform.

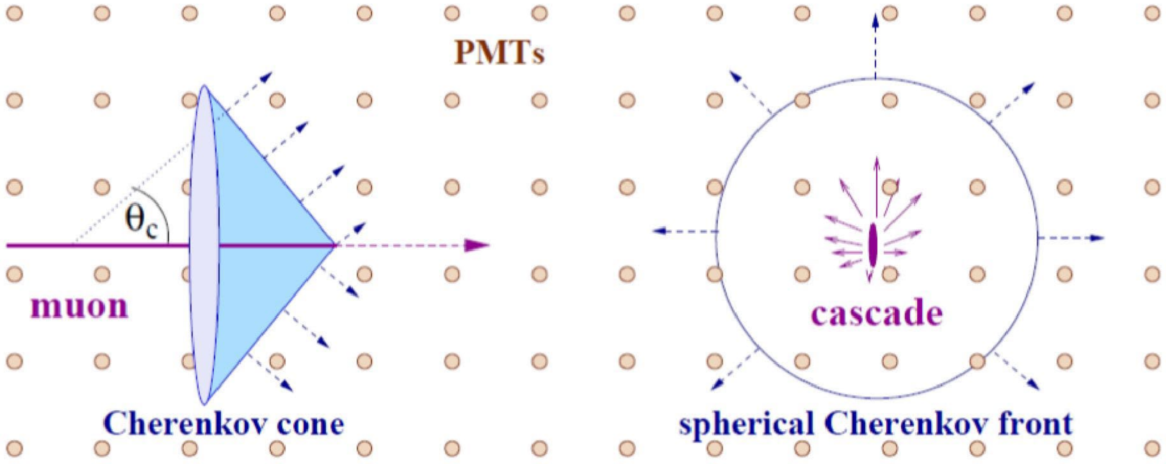


Figure 1: Detection principles for muon tracks (left) and cascades (right) in underwater detectors. Note that the Cherenkov light emission by cascades is peaked at the Cherenkov angle θ_c *with respect to the cascade axis but has a wide distribution covering the full solid angle.*

The astrophysical neutrino fluxes are investigated with neutrino telescopes in two main directions.

The first direction of research is concerned with the search for a neutrino signal from known astrophysical objects or the detection of unidentified local sources from observations of the signal excess above the background level over the entire celestial sphere. Figure 1 sketches the two basic detection modes of underwater neutrino telescopes. CC muon neutrino interactions produce a muon track (left), whereas other neutrino reaction types cause hadronic and/or electromagnetic cascades (right). This is, in particular, true for NC reactions (hadronic cascade) or CC reactions of electron neutrinos (overlapping hadronic and electromagnetic cascades). CC tau neutrino interactions can have either signature, depending on the τ decay mode.

Figure 2: The scheme of the OM and the OM production line in JINR.

The BAIKAL-GVD is 3 dimensional lattice of photomultiplier tubes each enclosed in a transparent pressure sphere to comprise an optical module (OM), fig. 2. The OMs are arranged on vertical load-carrying cables to form strings, fig. 4. The configuration of telescope consists of clusters of strings – functionally independent sub arrays, which are connected to shore by individual electro-optical cables.

Figure 3: Assembling the Baikal-GVD installation cluster garland.

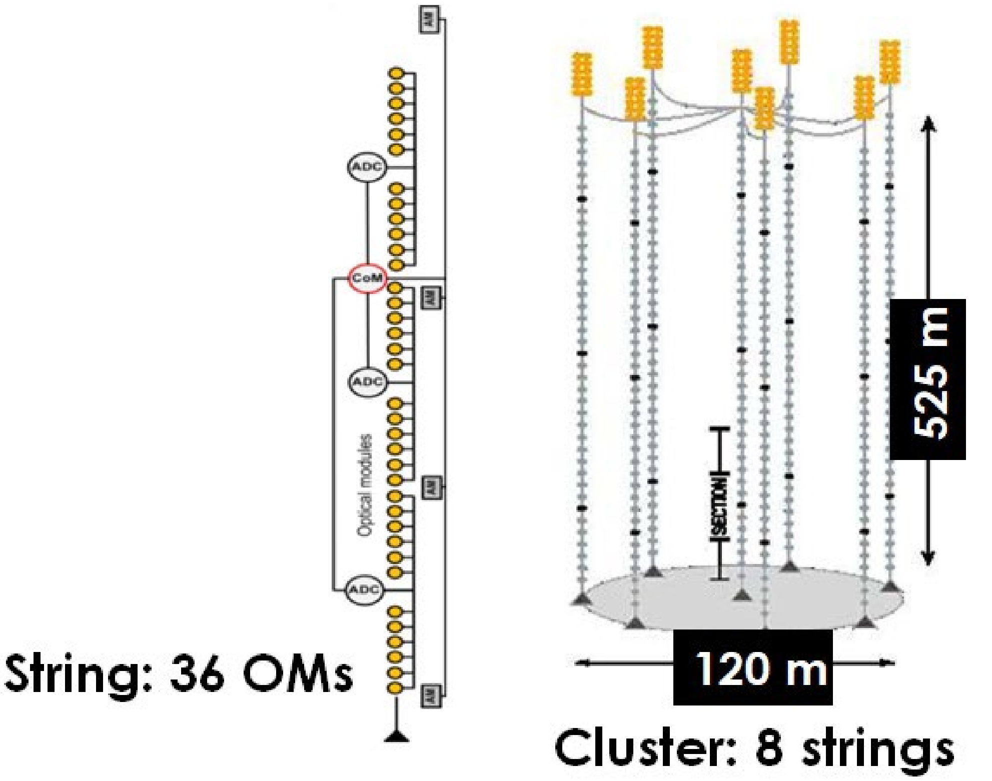


Figure 4: OM arrangements in the BAIKAL-GVD clusters.

Each cluster comprises eight strings of optical modules - seven peripheral strings are uniformly arranged at a 60 m distance around a central one. Optical modules are spaced by 15 m along each string and are faced downward. OMs on each string are combined in sections - detection units of telescope.

Each BAIKAL-GVD cluster is a functionally complete and independent sub-array, which can operate both as a part of unified configuration and autonomously. This allows for easy upgrade of the array configuration, as well as putting into operation its individual parts within the telescope deployment phase. The basic configuration of BAIKAL-GVD cluster comprises eight strings, a data acquisition center (DAQ-center), and electro-optical cable, which connects the cluster to the shore station (see Fig. 5). The DAQ-center of a cluster consists of 3 underwater modules, located at a shallow depth of about 30 m: a cluster communication center, a PC sphere, and an optical cable clutch.

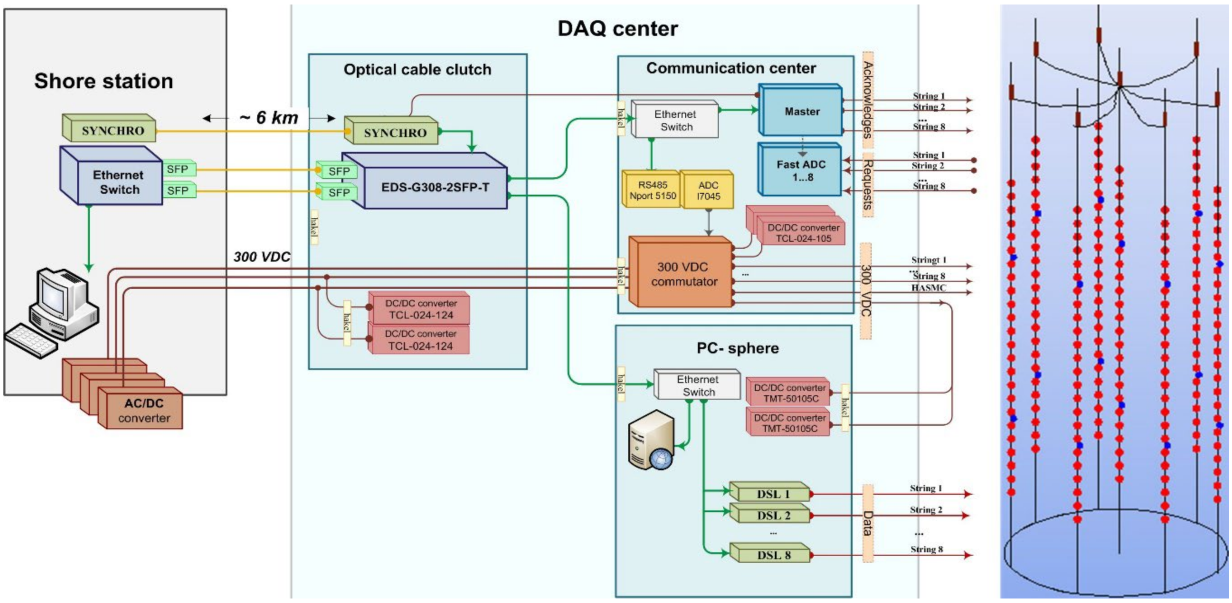


Figure 5: Functional scheme of the data acquisition center of a cluster (on the left) and a cluster composed of eight strings (on the right).

Strings are connected to the DAQ-center of cluster through 1.2 km long cables, which serve to transfer data, supply power, and synchronize the operation of sections. The cluster DAQ-center is connected to the shore by an electro-optical cable about 6 km long. This cable serves to feed the cluster and transfer digital data through a gigabit optical fiber communication line.

The present stage of the Baikal-GVD in Lake Baikal is the result of extensive research work carried out by the Baikal Collaboration in the previous phases of the project. Within the framework of the Seven-Year for 2017–2023, 12 clusters of the Baikal-GVD facility were put into operation (fig. 6), and by 2025, the first stage of the creation (deployment) of the entire detector with an effective working volume of more than 0.5 km^3 will be completed.

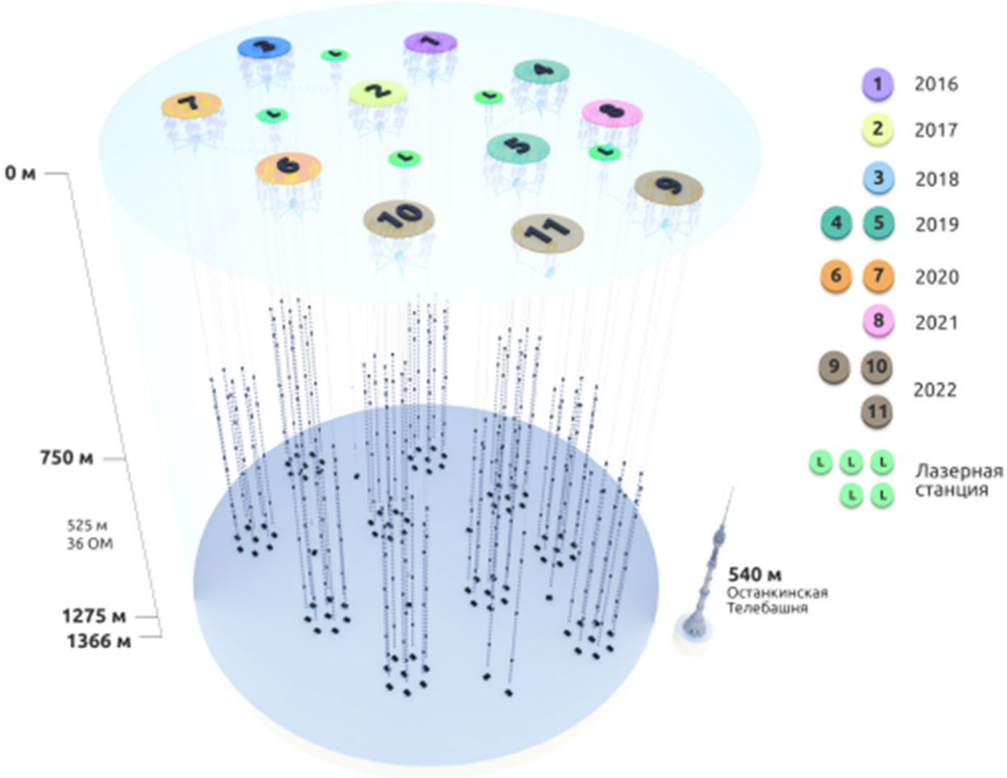


Figure 6: Telescope deployment status as of late 2022. The setup contains 2916 optical modules and seven laser calibration light sources at five stations.

Expected results:

In the second phase of its development (within the seven-year period of 2024-2030), the Baikal-GVD neutrino telescope will be a new research infrastructure aimed primarily at studying astrophysical neutrino fluxes. The detector will use Baikal water as a detecting substance, in which optical sensors are placed that register the Čerenkov radiation from secondary particles resulting from interactions of high-energy neutrinos inside the working volume of the detector or in close proximity to it. The concept of the Baikal-GVD facility is based on a number of fairly obvious requirements for the design and architecture of a system for collecting information from a distributed array of detecting clusters. These are the utmost use of the advantages of array deployment on the ice cover of the Lake, the extendibility of the facility and provision of its constant effective operation, as well as the possibility of various versions of arrangement of light sensors within one measuring system.

In the coming years, a new strategy for the development of the large-scale Baikal-GVD research complex will be intensively considered. The second phase of the Baikal-GVD neutrino telescope, the implementation of this new strategy, will begin at the turn of 2025 and is scheduled for completion in 2030, when the facility will have more than 20 clusters (approximately 6000-7000 optical modules) with an effective working volume of about or above one cubic kilometer.

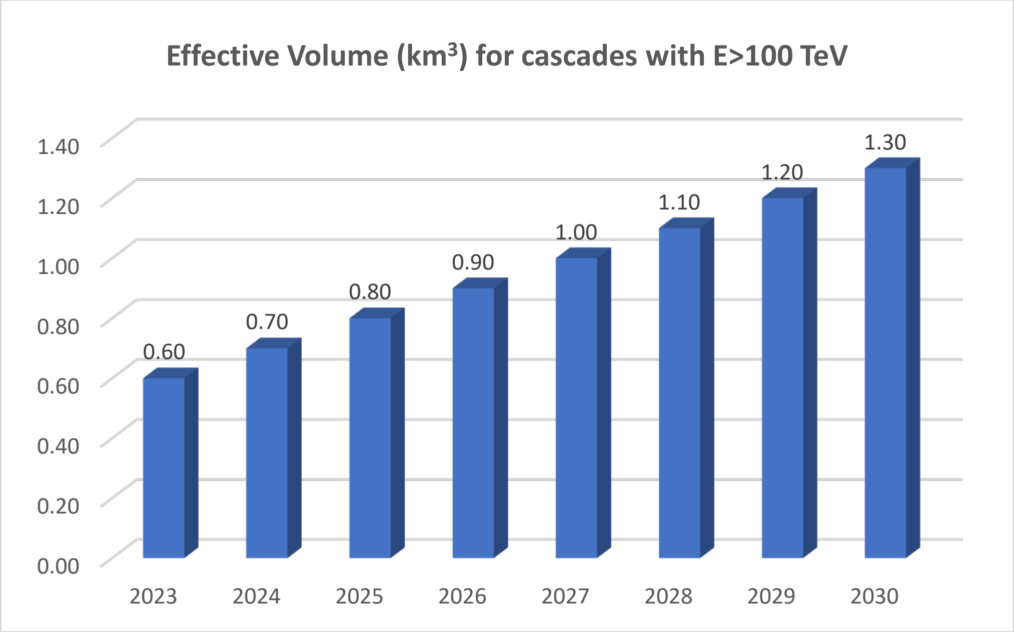


Figure 6: The Baikal-GVD experiment. Detector expansion plan in terms of effective volume in the problem of astrophysical flow detection

The speed of gathering statistics will be close to that of IceCube. This will allow us to study and, in a certain sense, control the entire outer space at the same statistical level. Given the advantages of the Northern Hemisphere for observing the center of our Galaxy, it is expected that this will allow the Baikal-GVD telescope to outpace IceCube in obtaining critical information about what is happening in this center. In fact, this means that Baikal-GVD will become not only a full-fledged, but also the most important link in the Global Neutrino Network.

A detector volume of 1 km^3 means a significant increase in the number of clusters, and their large number opens up the possibility of a systematic study of multicluster neutrino events, in particular, events caused by ultrahigh-energy τ neutrinos, since the topology of such events is characterized by a noticeable increase in the width of the expansion cone of products of interaction of τ neutrinos with nuclei.

Contribution of JINR Members

JINR Members are playing significant roles in all key parts of the BAIKAL-GVD experiment:

- Assembly and test of OMs and strings;
- Participation in winter deployment campaigns;
- Access and security service;
- Data archive processing and analysis;
- Detector calibration and mass processing of data;
- Remote control and monitoring systems of detector;
- Simulation software and MK production;
- On-line software;
- Development of new methods of event selection and reconstruction;
- Data analysis with respect to high-energy neutrinos and neutrinos from dark matter annihilation.

2.3 Estimated completion date

The project will be continued during the coming 7-years and definitely beyond.

2.4 Participating JINR laboratories

Dzhelepov Laboratory of Nuclear Problem
Laboratory of Information technologies

2.4.1 MICC resource requirements

Computing resources	**Distribution by year**				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes	 1.2 3000	 1.4 3500	 1.6 4000	 1.8 4500	 2.0 5000
Tier 1 (core-hour)					
Tier 2 (core-hour)	1M	1M	1.5M	1.5M	1.5M
SC Govorun (core-hour) - CPU - GPU	 1M	 1M	 1.5M	 1.5M	 1.5M
Clouds (CPU cores)	600	900	1200	1500	1800

2.5. Participating countries, scientific and educational organisations

Organisation	**Country**	**City**	**Participants**	**Type of agreement**
Institute for Nuclear Research of the Russian Academy of Sciences	Russia	Moscow	26	protocol
Comenius University	Slovakia	Bratislava	4	Collaboration memorandum
Irkutsk State University	Russia	Irkutsk	8	Collaboration memorandum
Institute of Nuclear Physics ME RK	Kazakhstan	Almaty	2	Collaboration memorandum
Czech Technical University	Czech Republic	Prague	2	Collaboration memorandum
Skobeltsyn Research Institute of Nuclear Physics, Moscow State University	Russia	Moscow	5	Collaboration memorandum
Nizhny Novgorod State Technical University	Russia	Nizhny Novgorod	1	Collaboration memorandum

Saint Petersburg State Marine Technical University	Russia	Saint Petersburg	1	Collaboration memorandum

2.6. Co-executing organisations *(those collaborating organizations/partners without whose financial, infrastructural participation the implementation of the research programme is impossible. An example is JINR's participation in the LHC experiments at CERN).*

INR RAS, Moscow

3. Staffing

3.1. Staffing needs in the first year of implementation

№№ n/a	**Category employee**	**Core staff, Amount of FTE**	**Associated Personnel Amount of FTE**
1.	scientific staff	9.75	
2.	engineers	14.75	
3.	professionals	3.6	
4.	workers	4.3	
	Total:	**32.4**	

3.2. Human resources available
3.2.1. JINR core staff (only personal related to the theme 1100)

№№ п/а	Category of employees	NAME	Division	Position	Amount of FTE
1.	scientific staff	Belolaptikov I.	DLNP	BAIKAL-GVD setup manager	1
		Dik V.		junior scientist	1
		Konishev K.		research scientist	1
		Pliskovski E.		research scientist	1
		Seitova D.		junior scientist	1
		Sorokovikov M.		junior scientist	1
		Shaibonov B.		senior scientist	1
		Rozov S.		deputy head of department	0.1
		Sandukovskiy V.		consultant at the directorate of the DLNP	0.25
		Yakushev E.		head of department	0.3
		Doroshenko A.		research scientist	0.5
		Safronov G.		senior scientist	0.5
		Naumov D.		deputy director of the DLNP	0.3
		Solovjev A.	LIT	senior scientist	0.8
2.	engineers	Allakhverdyan V.	DLNP	engineer	1
		Antonov P.		engineer	0.5
		Borina I.		senior engineer	1
		Dotsenko I.		senior engineer	0.8
		Elzhov T.		lead engineer	1
		Golubkov K.		senior engineer	0.5
		Gorshkov N.		engineer	1
		Kalinova B.		engineer	0.3
		Kamnev I.		engineer	0.2
		Katulin S.		senior engineer	0.7
		Katulina S.		senior engineer	0.3
		Korobchenko A.		senior engineer	1
		Kruglov M.		senior engineer	1
		Minaev M.		engineer	1
		Petukhov D.		engineer	0.5
		Sherbakova I.		engineer	0.1
		Shevchenko M.		engineer	0.1
		Sirenko A.		engineer	1
		Stromakov A.		senior engineer	0.5
		Volnykh V.		lead engineer	0.25
		Yablokova Yu.		engineer	1
		Zvezdov D.		engineer	1
3.	professionals	Kulkova E.	DLNP	document management specialist	0.7
		Lednicka T.		laboratory assistant	0.1
		Morozova T.		senior inspector	0.3

		Orlov D. Shevchenko S. Ulzutuev B.		laboratory assistant laboratory assistant laboratory assistant	1 1 0.5
4.	workers	Emeliyanov A. Kolbin M. Shevchenko K. Sosunov N. Stepkin I. Zaikin A.	DLNP	mechanic-repairman mechanic of experimental stands and setups welder mechanic technician mechanic of experimental stands and setups	0.1 1 0.5 1 1 0.7
	Total:				**32.4**

4. Financial support

4.1 Total estimated cost of the project/sub-project of the LRIP

Forecast of the total estimated cost (specify cumulatively for the whole period, excluding FPC). The details are given in a separate form.

38550 k$

Project (sub-project of the LRIP) Leader __________/___________/

Date of submission of the project (sub-project of the LRIP) to DSOA: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project (subproject of the LRIP) opening: ________________

(for renewable projects) -- Project start year: _______

Schedule proposal and resources required for the implementation of the Project / Sub-project of the LRIP

Names of costs, resources, sources of funding			**Cost (thousands of dollars) resource requirements**	**Cost, distribution by year**				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation (IC)	750	150	150	150	150	150
		Materials	27 500	5700	5700	5700	5200	5200
		Equipment and third-party services (commissioning)	4 300	800	800	900	900	900
		Commissioning work	1000	200	200	200	200	200
		Services of research organizations	500	100	100	100	100	100
		Acquisition of software						
		Design/construction	2 000	400	400	400	400	400
		Service costs (*planned in case of direct project affiliation)*	2 500	400	450	500	550	600
Resources required	**Normo-hours**	Resources						
		– the amount of FTE,	25 000	5000	5000	5000	5000	5000
		– accelerator/installation,						
		– reactor,….						
Sources of funding	**Budgetary resources**	JINR budget *(budget items)*	36 050	7250	7300	7450	7000	7050
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors	2 500	500	500	500	500	500
		Funds under contracts with customers						
		Other sources of funding						

Project (sub-project of the LRIP) Leader_________/________________/

Laboratory Economist _________/________________/

APPROVAL SHEET FOR PROJECT

NAME OF THE PROJECT/SUBPROJECT OF THE LRIP: **BAIKAL-GVD, Deep underwater muon and neutrino detector on Lake Baikal (Gigaton Volume Detector)**

DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/SUBPROJECT OF THE LRIP CODE

THEME / LRIP CODE: **03-2-1100-2010/2024**

NAME OF THE PROJECT/ SUBPROJECT OF THE MIP LEADER: **Igor Belolaptikov**

AGREED			
JINR VICE-DIRECTOR	____________ SIGNATURE	____________ NAME	____________ DATE
CHIEF SCIENTIFIC SECRETARY	____________ SIGNATURE	____________ NAME	____________ DATE
CHIEF ENGINEER	____________ SIGNATURE	____________ NAME	____________ DATE
LABORATORY DIRECTOR	____________ SIGNATURE	____________ NAME	____________ DATE
CHIEF LABORATORY ENGINEER	____________ SIGNATURE	____________ NAME	____________ DATE
LABORATORY SCIENTIFIC SECRETARY	__________ SIGNATURE	____________ NAME	____________ DATE
THEME LEADER	__________ SIGNATURE	____________ NAME	____________ DATE
PROJECT LEADER	___________ SIGNATURE	____________ NAME	____________ DATE
APPROVED BY THE PAC	____________ SIGNATURE	____________ NAME	____________ DATE

Scientific report

Annotation

The Baikal-GVD neutrino telescope study the most violent processes in the Universe, which accelerate charged particles to highest energies, far beyond the reach of laboratory experiments on Earth. These processes must be accompanied by the emission of neutrinos. The large detection volume, combined with high angular and energy resolution and moderate background conditions in fresh lake water allows for an efficient study of the diffuse neutrino flux and of neutrinos from individual astrophysical objects, be they steady or transient. Multi-messenger methods is start to be used to relate our findings with those of classical astronomers and with X-ray or gamma-ray observations. A high-energy diffuse astrophysical neutrino flux that has been observed recently by IceCube, using track-like and cascade-like events was confirmed by the Baikal-GVD.

Main scientific results

With the commissioning of two new clusters in April 2022, the working volume of the Baikal deep-sea neutrino telescope Baikal-GVD reached a value of ≈0.4 cubic km this year in the task of recording events from high-energy neutrinos (over 100 TeV).

The detector contains 10 clusters of deep-sea garlands of recording and control equipment (2916 optical modules) and is the largest neutrino telescope in the Northern Hemisphere. In February-March 2023 two more clusters are start to be deployed. About 700 optical modules were assembled for deployment in 2023. The collaboration is going to install additional two new clusters under favorable external conditions (weather and ice). Figure 8 shows progress in the detector building.

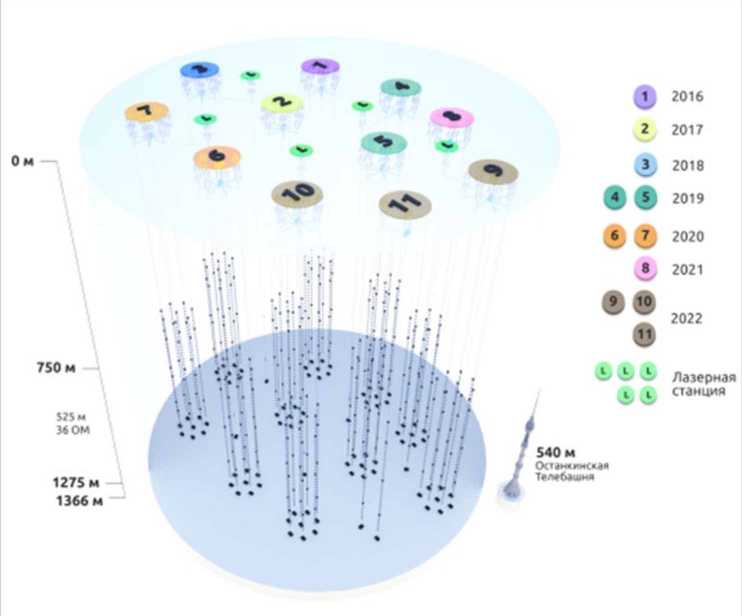
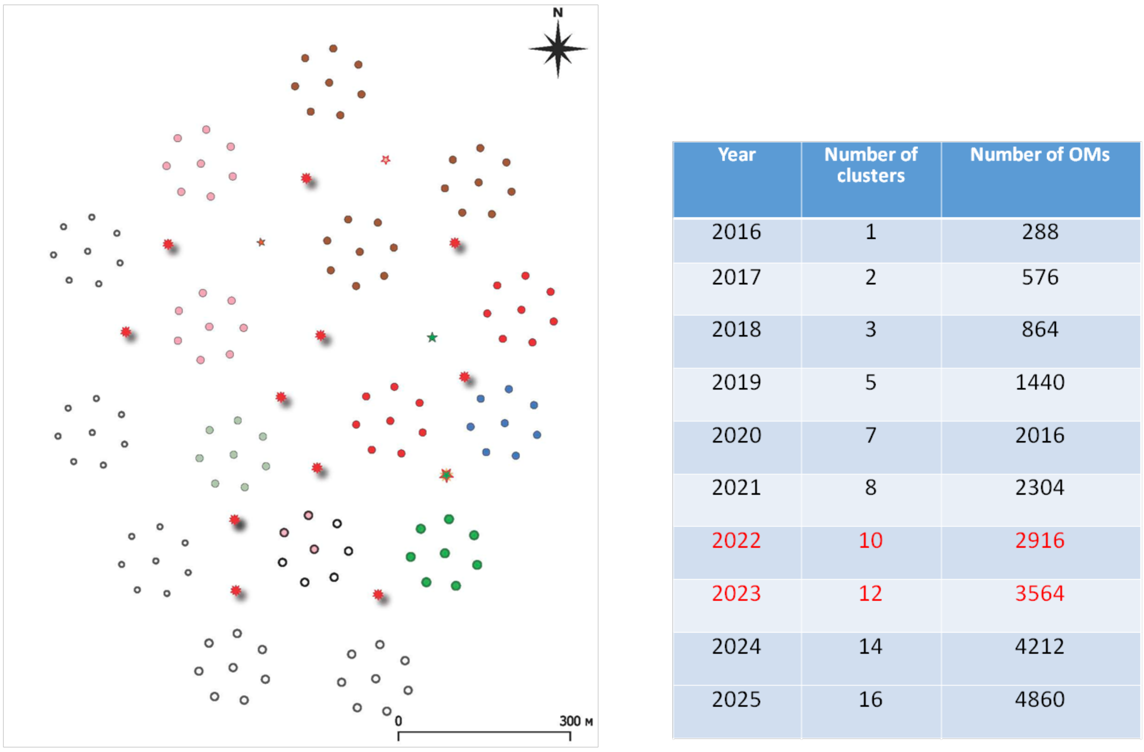


Figure 7: Baikal-GVD in 2022. The array contains 2916 optical modules.



Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2916
2023	12	3564
2024	14	4212
2025	16	4860

Figure 8: Baikal-GVD deployment 2016-2025.

When analyzing the data obtained during the operation of the detector in the configurations of 2018 - 2021, 11 cascading events with an energy of over 15 TeV from under the horizon, initiated by neutrinos of astrophysical nature, were selected, which at a confidence level of 3σ confirms the results of the first observation of the flux of high-energy astrophysical neutrinos on the Antarctic detector IceCube.

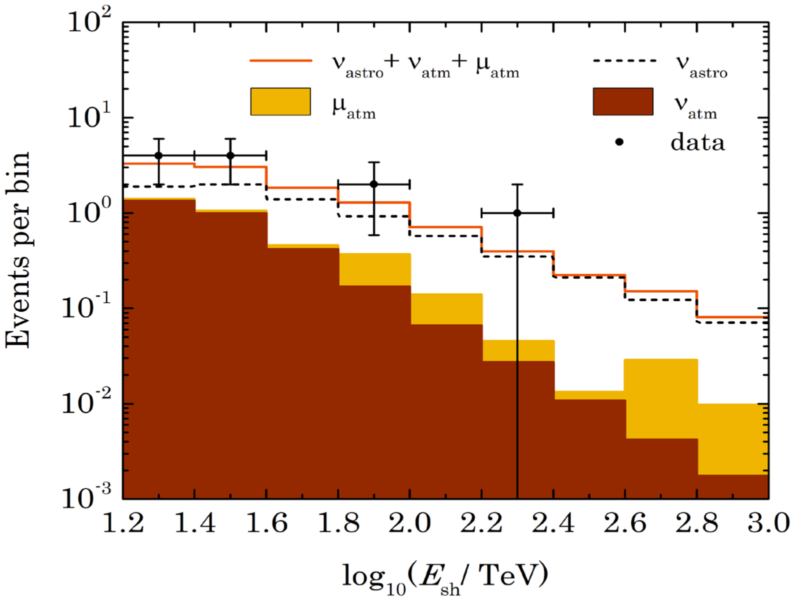


Figure 9: Energy distributions of experimental and theoretically expected events in the analysis of cascade events from under the horizon: experimental events - black dots; the distribution of events expected from the diffuse neutrino flux of astrophysical nature with parameters obtained from the Baikal-GVD data for 2018-2021 - dotted histogram; background events from atmospheric muons and atmospheric neutrinos - stacked yellow and brown painted areas; the total number of expected signal and background events is an orange histogram.

Diffuse neutrino flux measurements with the Baikal-GVD neutrino telescope has been just published [*Physical Review D* 107.4, 2023].

JINR participation and main facilities

JINR Members are playing significant roles in all key parts of the BAIKAL experiment:

- Assembly and test of OMs and strings
- Participation in winter deployment campaigns
- Access and security service.
- Data archive processing and analysis.
- Detector calibration and mass processing of data.
- Remote control and monitoring systems of detector
- Simulation software and MK production.
- On-line software
- Development of new methods of event selection and reconstruction.
- Data analysis with respect to high-energy neutrinos and neutrinos from dark matter annihilation.

One of the main Baikal-GVD facilities: the line for assembly of OM was created at JINR (figure 10). Additional facilities for long-term tests of the detector components (strings) were also recently prepared on the JINR site.

Figure 10: Baikal-GVD optical module assembly line.

At Baikal site JINR plays an important role in creation of general experimental infrastructure, which includes facilities for detector deployment and maintenance, data acquisition, logistic and networking, allocation of personal, etc.

Publications (last 5 years)

Allakhverdyan, V.A.. "Diffuse neutrino flux measurements with the Baikal-GVD neutrino telescope." *Physical Review D* 107.4, 2023, ISSN 2470-0010, https://doi.org/10.1103/PhysRevD.107.042005
Avrorin, A.V.. "Deep-Underwater Cherenkov Detector in Lake Baikal." *Journal of Experimental and Theoretical Physics* 134.4, 2022, pp. 399-416., ISSN 1063-7761, https://doi.org/10.1134/S1063776122040148
Safronov, G.. "Performance of the muon track reconstruction with the Baikal-GVD neutrino telescope." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "The Baikal-GVD neutrino telescope: search for high-energy cascades." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Positioning system for Baikal-GVD." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Kopański, K.. "Method and device for tests of the laser optical calibration system for the Baikal-GVD underwater neutrino Cherenkov telescope." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Data Quality Monitoring system of the Baikal-GVD experiment." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Technique for suppression of background cascades produced by atmospheric muon bundles in the Baikal-GVD." *Journal of Instrumentation* 17.2, 2022, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/17/02/C02013
Garre, S. Alves. "ANTARES offline study of three alerts after Baikal-GVD follow-up found coincident cascade neutrino events." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Experimental string with fiber optic data acquisition for Baikal-GVD." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Time synchronization of Baikal-GVD clusters." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Methods for the suppression of background cascades produced along atmospheric muon tracks in the Baikal-GVD." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "The Baikal-GVD neutrino telescope as an instrument for studying Baikal water luminescence." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "An efficient hit finding algorithm for Baikal-GVD muon reconstruction." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Ryabov, E.. "Monitoring of optical properties of deep lake water." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Automatic data processing for Baikal-GVD neutrino observatory." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Development of the Double Cascade Reconstruction Techniques in the Baikal-GVD Neutrino Telescope." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Observations of track-like neutrino events with Baikal-GVD." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Allakhverdyan, V.A.. "Multi-messenger and real-time astrophysics with the Baikal-GVD telescope." *Proceedings of Science* 395, 2022, ISSN 1824-8039
Avrorin, A.D.. "High-Energy Neutrino Astronomy and the Baikal-GVD Neutrino Telescope." *Physics of Atomic Nuclei* 84.4, 2021, pp. 513-518., ISSN 1063-7788, https://doi.org/10.1134/S1063778821040062
Allakhverdyan, V.A.. "Measuring muon tracks in Baikal-GVD using a fast reconstruction algorithm." *European Physical Journal C* 81.11, 2021, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-021-09825-y
Avrorin, A.V.. "High-Energy Neutrino Follow-up at the Baikal-GVD Neutrino Telescope." *Astronomy Letters* 47.2, 2021, pp. 94-104., ISSN 1063-7737, https://doi.org/10.1134/S1063773721020018
Avrorin, A.D.. "The optical noise monitoring systems of the Lake Baikal environment for the Baikal-GVD telescope." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Allakhverdyan, V.A.. "Deep-Water Neutrino Telescope in Lake Baikal." *Physics of Atomic Nuclei* 84.9, 2021, pp. 1600-1609., ISSN 1063-7788, https://doi.org/10.1134/S1063778821090064

Avrorin, A.D.. "Search for cascade events with Baikal-GVD." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Avrorin, A.D.. "The Baikal-GVD detector calibrations." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Dik, V.Y.. "Follow-up of the IceCube alerts with the Baikal-GVD telescope." *Journal of Instrumentation* 16.11, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/11/C11008

Allakhverdyan, V.A.. "Time synchronization system of Baikal-GVD." *Journal of Instrumentation* 16.9, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/09/C09003

Avrorin, A.D.. "Baikal-GVD: Status and first results." *Proceedings of Science* 390, 2021, ISSN 1824-8039

Avrorin, A.D.. "Neutrino Telescope in Lake Baikal: Present and Future." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Avrorin, A.D.. "A positioning system for Baikal-GVD." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Avrorin, A.D.. "The inter-cluster time synchronization systems within the Baikal-GVD detector." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Avrorin, A.D.. "The Baikal-GVD neutrino telescope: First results of multi-messenger studies." *Proceedings of Science* 358, 2021, ISSN 1824-8039

Allakhverdyan, V.A.. "Method and portable bench for tests of the laser optical calibration system components for the Baikal-GVD underwater neutrino Cherenkov telescope." *Journal of Instrumentation* 16.12, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/12/C12011

Allakhverdyan, V.A.. "Luminescence of Baikal water as a dynamic background of the Baikal-GVD Neutrino Telescope." *Journal of Instrumentation* 16.11, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/11/C11011

Allakhverdyan, V.A.. "Proposal for fiber-optic data acquisition system for Baikal-GVD." *Journal of Instrumentation* 16.11, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/11/C11006

Avrorin, A.V.. "Calibrating the Measuring Channels of the Baikal-Gvd Neutrino Telescope." *Instruments and Experimental Techniques* 63.4, 2020, pp. 551-560., ISSN 0020-4412, https://doi.org/10.1134/S0020441220040107

Sinegovsky, S.I.. "Prompt atmospheric neutrinos in the quark–gluon string model." *European Physical Journal C* 80.1, 2020, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-019-7547-0

Avrorin, A.D.. "BAIKAL-GVD: The New-Generation Neutrino Telescope in Lake Baikal." *Bulletin of the Russian Academy of Sciences: Physics* 83.8, 2019, pp. 921-922., ISSN 1062-8738, https://doi.org/10.3103/S1062873819080057

Avrorin, A.D.. "Search for cascade events with Baikal-GVD." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "Data quality monitoring system in the baikal-gvd 2 experiment." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "Recent progress of the Baikal-GVD project." *Proceedings of Science* 364, 2019, ISSN 1824-8039

Avrorin, A.D.. "Data quality monitoring system in the Baikal-GVD experiment." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "The Baikal-GVD neutrino telescope: First results of multi-messenger studies." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "The optical noise monitoring systems of the Lake Baikal environment for the Baikal-GVD telescope." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "A positioning system for Baikal-GVD." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "The inter-cluster time synchronization systems within the Baikal-GVD detector." *Proceedings of Science* 358, 2019, ISSN 1824-8039

Avrorin, A.D.. "The Baikal-GVD detector calibrations." *Proceedings of Science* 358, 2019, ISSN 1824-8039
Avrorin, A.D.. "Neutrino telescope in Lake Baikal: Present and future." *Proceedings of Science* 358, 2019, ISSN 1824-8039
Sinegovsky, S.. "The atmospheric neutrino flux from decays of charmed particles." *Journal of Physics: Conference Series* 1181.1, 2019, ISSN 1742-6588, https://doi.org/10.1088/1742-6596/1181/1/012055
Avrorin, A.D.. "Baikal-GVD: Status and prospects." *EPJ Web of Conferences* 191, 2018, ISSN 2101-6275, https://doi.org/10.1051/epjconf/201819101006
Avrorin, A.D.. "Search for High-Energy Neutrinos from GW170817 with the Baikal-GVD Neutrino Telescope." *JETP Letters* 108.12, 2018, pp. 787-790., ISSN 0021-3640, https://doi.org/10.1134/S0021364018240025

Conferences (2021-2022) with JINR group participations:
2021:
Very Large Volume Neutrino Telescope Workshop, https://indico.ific.uv.es/event/3965/
B. Shaibonov, Yu. Yablokova, T. Elzhov, M. Sorokovikov, G. Safronov, I. Belolaptikov

37th International Cosmic Ray Conference, https://icrc2021.desy.de/
B. Shaibonov, M. Sorokovikov, G. Safronov, I. Belolaptikov, R. Dvornicki

2022:
14th International School on Neutrino Physics and Astrophysics, Sarov, June 18-23 2022, D. Seitova
37-я Всероссийская конференция по космическим лучам, Москва, 27 июня - 2 июля, 2022, M. Sorokovikov, V. Dik.
The 27th European Cosmic Ray Symposium (ECRS 2022), Nijmegen, the Netherlands (online participation), 25-29 июля 2022, V. Dik.
The IV International Scientific Forum “Nuclear science and Technologies”, D. Seitova

JINR grants (scholarships) received.

Competition for JINR Young Scientists and Specialists (2021-2023): 8 in total for last 3 years
Seitova D., Sorokovikov M, Kolbin M (twice), Sirenko A., Gorshkov N, Kruglov M., Shevchenko S.

Theme / LRIP Leader

_____________/_____________/
"_____"__________________ 2023

Project leader (project code) / sub-project of the LRIP
_____________/_____________/
"_____"__________________ 2023