**APPROVED**

**JINR VICE-DIRECTOR**

**/ /**

**“ “ 202**\_ **г.**

**SCIENTIFIC AND TECHNICAL SUBSTANTIATION OF OPENING / EXTENSION**

**PROJECT / MAJOR INFRASTRUCTURE PROJECT ON THE**

**DIRECTION OF RESEARCH IN THE THEMATIC PLAN OF JINR**

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

**1.1. Theme code / LRIP**

*1099-2023/2025*

**1.2. Laboratory**

DLNP

**1.3. Scientific field**

Particle physics

**1.4. Title of the Theme/LRIP**

Astrophysical research in the TAIGA experiment

**1.5. Theme / LRIP Leader(s)**

A. Borodin

**1.6. Theme / LRIP Deputy Leader(s)**

L. Tkachev

# 2. Scientific case and project organization

## 2.1. Annotation for the TAIGA project

TAIGA Astrophysical Complex (**T**unka **A**dvanced **I**nstrument for cosmic ray physics and

**G**amma-ray **A**stronomy) is designed to study the gamma radiation of charged cosmic rays in

the energy range 1013− 1018 eV by the method of registration of Cherenkov radiation from

extensive air showers (EAS) and is located in the Tunka Valley (51.49 N, 103.04 E), 50 km from Lake Baikal.

The complex includes a unique system of hybrid detectors - 3 atmospheric Cherenkov

telescopes (ACT) and two wide-angle EAS Cherenkov arrays - Tunka-133 and TAIGA-HiSCORE

with an effective area of 3 km2 and 1 km2 respectively, and two setups for detecting charged

cosmic rays - Tunka-Grande and Tunka-Muon

## 2.2. Scientific case

Astrophysical research in the TAIGA experiment

The key idea is to combine in one complex two radically different methods for

detecting EAS Cherenkov radiation (imaging and non-imaging (timing)), namely: IACT( **I**maging **A**tmosphere **C**herenkov **T**elescope) - telescopes that image extensive air showers (EAS) by registering Cherenkov radiation and wide-angle Cherenkov detectors. The main advantage of the operation of a IACT jointly with wide-angle Cherenkov detectors is the possibility of separating events from gamma rays against of EAS from charged cosmic rays according to the data of one or several IACT using information about the energy, position and direction of the EAS axis, reconstructed from the data of a wide-angle installation. The main areas of research of the complex include the problems of gamma astronomy and cosmic ray physics:

**1. Investigate the energy spectrum of gamma rays from Galactic sources and search for new gamma ray sources.** The plan is to reconstruct the gamma-ray spectrum quanta from galactic sources (Crab Nebula, Dragonfly, J2227+610(G106.3+2.7), J2031+415(CygnusCocoon), Tycho-Brahe supernova) important for understanding the origin of cosmic rays.

**2. Monitoring gamma ray flux from nearby extragalactic sources.** Studying the shape of the spectrum of gamma-quanta with energies above 8 TeV from extragalactic sources will make it possible to obtain restrictions on the density of extragalactic background radiation(EBL) and to search for "axion-like" particles.

**3. Search for TeV gamma-rays from gamma-ray burst and gamma-rays, correlated with high-energy neutrinos.**

**4. Search for space accelerators in which protons are accelerated to energies of 100-3000 TeV.** To search for such accelerators, we will study the features of the spectrum charged cosmic rays in the energy range 100-3000 TeV. The proportion of protons and helium among the nuclei of charged cosmic rays will be measured.

**5. Study of the mass composition of cosmic rays in the transition region from galactic to extragalactic rays**

TAIGA is currently the world's northernmost gamma-ray observatory Fig.1. The

observation program of the observatory includes sources whose observation time is long enough for the northern location of the observatory: the Crab Nebula, Dragonfly, Tycho-Brahe supernova remnants, CTA-1, G106.3+2.7, sources in the SygnysCocoon nebula, blazars Мrk501, Mrk421, etc. The operation of Cherenkov telescopes and the wide-angle detectors, in addition to research in the field of gamma-ray astronomy, will make it possible to advance in the study of the characteristics of the mass composition of cosmic rays in an energy region that has not been sufficiently studied in direct experiments on satellites.

Project risks associated with the lack of funding for the expansion of competing gamma-ray astronomy projects around the world and with possible delays when replacing inaccessible components with equivalent ones available when designing new Cherenkov telescopes (both small wide-angle telescopes and those with a large area of the primary mirror).

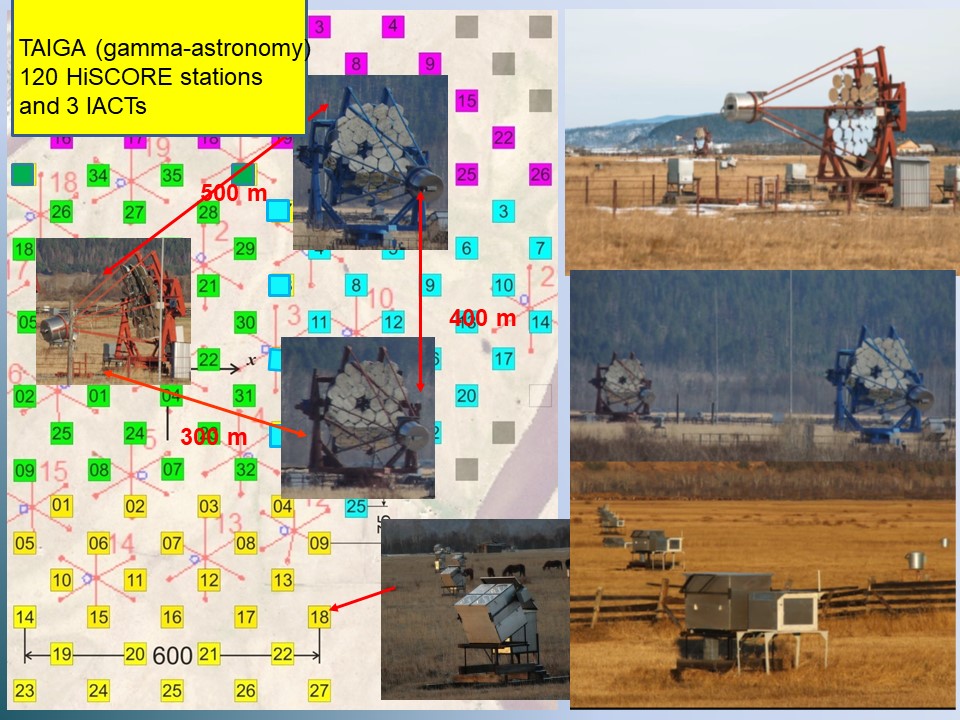


Fig. 1 Layout plan of the detectors of the TAIGA complex. Colored squares are HiSCORE

stations.

**Astrophysical Complex Development Program**

The immediate development of the TAIGA astronomical complex is associated with the creation of two more atmospheric Cherenkov telescopes and a significant increase in the area of muon detectors (the TAIGA-MUON facility).

One of the shortcomings of the hybrid approach in the existing version of the astrophysical complex is the significant difference between the angular aperture of the Cherenkov telescopes and the aperture of the TAIGA-HiSCORE facility, leading to the possibility of observing only one source at a given time. To correct this situation, it is planned to create small imaging Cherenkov telescopes (SIT) with an angular aperture of 25-30 degrees and an energy threshold of 80-100 TeV. The joint operation of such telescopes and the TAIGA-HiSCORE detectors will increase the number of hybrid events by

almost 10 times, for which it is possible to extract gamma rays from the background of events. Further development of the astrophysical complex, most likely elsewhere.

# 2.4. Participating JINR laboratories

DLNP, VBLHEP, FLNP, LIT

# 2.4.1. MICC resource requirements

|  |  |  |  |
| --- | --- | --- | --- |
| **Computing resources** | **Distribution by year** | | |
| 1st year | 2nd year | 3rdyear |
| Data storage (TB)  - EOS  - Tapes | 20 | 20 | 20 |
| Tier 1 (CPU core hours) | - |  |  |
| Tier 2 (CPU core hours) | - |  |  |
| SC Govorun (CPU core hours)  - CPU  - GPU | - |  |  |
| Clouds (CPU cores) | 200 | 200 | 200 |

# 2.5. Participating countries, scientific and educational organizations

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| JINR | Russia | Dubna | A.N. Borodin  V.M. Grebenyuk  A.V. Blinov  A.A Grinuyk  M.V. Lavrova  A. Pan  I. Satyshev  L.G. Tkachev  A.B.Sadovsky  N.V.Gorbunov  S.Yu.Porohovoi  L.G. Tkachev  H.Karatash  E.Sholtan  A.Shaikovsky  А.Pan  S.Satyshev  A.D.Rogov  А.V.Krasnoperov | Agreement on creation consortium GAMMA |
| Skobeltsyn Institute of Nuclear Physics MSU | Russia | Moscow | L.A. Kuzmichev  L.G. Sveshnikova  +15 pers.  P.A.Klimov  +5 pers.  D.M.Podorozhny  + 10 pers. | Agreement on creation consortium GAMMA, agreement on cooperation |
| Institute of Applied Physics, ISU, | Russia | Irkutsk | N.M. Budnev  R.Mirgazov  D.P. Zhurov  + 29 pers. | Agreement on creation consortium GAMMA, agreement on cooperation |
| Institute for Nuclear Research of RAS, | Russia | Moscow | B.K.Lubsandorzhiev  + 5 pers | Agreement on creation consortium GAMMA |
| IZMIRAN, | Russia | Moscow Region | V.S. Ptuskin | Agreement on creation consortium GAMMA |
| National Research Nuclear University MEPhI, | Russia | Moscow | A.A. Petrukhin  I.I. Yashin + 5 pers. | Agreement on creation consortium GAMMA |
| Novosibirsk State University, NSU, | Russia | Novosibirsk, | E.A. Kravchenko  + 5 pers. | Agreement on creation consortium GAMMA |
| Budker Institute of Nuclear Physics SB RAS, | Russia | Novosibirsk, | E.A. Kravchenko  +4 pers. | Agreement on creation consortium GAMMA |
| Altai State University, | Russia | Barnaul | A.A. Lagutin  R.I. Raikin  N.V. Volkov | Agreement on creation consortium GAMMA |
| Italy | Italy | Turin | A. Chiavassa |  |
| Ulaanbaatar University | Mongolia | Ulaanbaatar | R. Togoo |  |
| Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan — conducting tests of prototypes of the INP reactor | Republic Kazakhstan | Almaty | Mukhamedzhanov  Yerzhan Serikovich + 5 pers. | Additional agreement № 1 JINR-INP Almaty |
|  | Russia | Korolev | О.Saprykin  +5 pers. |  |
| Myung-Jae Lee Department of Physics, Sungkyunkwan University (SKKU), Suwon, Korea. | Republic Korea | Suwon | I.Pack |  |

# 2.6. Key partners

1. Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia

- data processing and physical analysis, IACT camera fabrication, DAQ, MC-simulation

2. Institute of Applied Physics, ISU, Irkutsk, Russia

-Tunka infrastructure, data taken, control electronics for IACTs and Hi-SCORE, deployment of detectors, Hi-SCORE MC-simulation and data analysis

3. Institute for Nuclear Research of RAS, Moscow, Russia

- IACT camera fabrication, muon detectors

- Methodical question IACTs construction and calibration, data analysis, Hi-SCORE PMTs

HiSCORE and IACT MC-simulation

4. IZMIRAN, Moscow Region, Russia

- theoretical support

5. National Research Nuclear University MEPhI, Moscow, Russia

- data analysis, IACT camera fabrication , MC-simulation

6. JINR, Dubna, Russia

- full responsibility in the design, fabrication and tests of IACTs mechanics at

JINR, participation in the software development and Monte-Carlo simulation, in data taking in Tun ka area and in off-line analysis. Development and production of IACT mirror facets, IACT mirror actuator production,

7. Novosibirsk State University, NSU, Novosibirsk, Russia

- design and fabrication muon detectors

8. Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

- design and fabrication muon detectors

- IACT electronic components

9. AltaiStateUniversity, Barnaul, Russia

10. Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan

- Participation in the development and manufacture of a prototype OLVE-HERO, conducting MS simulation of the OLVE-HERO experiment, prototype tests at the NUCLOTRON, the INR

reactor and the Tien-Shan Alpine Space Station, and data processing.

11. SKB Avtomatika

- development and manufacture of detectors and electronics OLVE-HERO

12. JSC "Consortium "Space Regatta". Korolev, Moscow region.

- development, manufacture and testing of the optical system.

13. Myung-Jae Lee Department of Physics, Sungkyunkwan University (SKKU), Suwon, Korea.

- participation in the development and manufacture of a photodetector, collection and filtering electronics data, as well as creating a set of programs for off-line data analysis.

# 3. Manpower

## 3.1. Manpower need in the first year of implementation

|  |  |  |  |
| --- | --- | --- | --- |
| **№№ n/a** | **Category of personnel** | **JINR staff,**  **amount of FTE** | **JINR Associated**  **Personnel,**  **amount of FTE** |
| 1. | Research scientist | 4.8 |  |
| 2. | engineers | 4.7 |  |
| 3. | specialists | 1.0 |  |
| 4. | students | 2.0 |  |
| 5. | technicians |  |  |
|  | **Total:** | **12.5** |  |

## 3.2. Available manpower

### 3.2.1. JINR staff

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **№№ n/a** | **Category of personnel** | **Full name** | **Division** | **Position** | **Amount of FTE** |
| 1. | Research scientists | A.Borodin | DLNP | researcher | 1.0 |
|  |  | L. Tkachev | DLNP | researcher | 1.0 |
|  |  | N.Gorbunov | VDLHEP | researcher | 0.1 |
|  |  | A.Krasnoperov | DLNP | researcher | 0.1 |
|  |  | A.Rogov | FLNP | researcher | 0.1 |
|  |  | V. Grebenyuk | DLNP | researcher | 1.0 |
|  |  | M. Lavrova | DLNP | researcher | 1.0 |
|  |  | I.Satyshev | LIT | researcher | 0.5 |
| 2. | Engineers | A. Grinyuk | DLNP | engineer | 1.0 |
|  |  | A.Pan | DLNP | engineer | 1.0 |
|  |  | S. Porokhovoy | DLNP | engineer | 0.2 |
|  |  | A. Blinov | DLNP | engineer | 1.0 |
|  |  | A. Skrypnik | DLNP | engineer | 0.1 |
| 3. | Specialists | Y.Pavlov | DLNP | technician | 1 |
|  |  | A.Shaykovsky | DLNP | designer | 0.4 |
|  |  | E. Sholtan | DLNP | student | 1.0 |
|  |  | H. Karatash | DLNP | student | 1.0 |
| 4. | Workers |  |  |  |  |
|  | **Total:** |  |  |  | **12.5** |

### 3.2.2. JINR associated personnel

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | technicians |  |  |
|  | **Total:** |  |  |

# 4. Financing

4.1. **Total estimated cost of the project/LRIP subproject**

Forecast of the full estimated cost (indicate in total for the entire period, with the exception of the wage bill). The details are given in a separate form. **275 k$**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **№№**  **п/п** | **Name of works** | **Price, k$** | **Cost per year** | | |
| 1st year | 2nd year | 3d year |
| 1. | International cooperation (ISTS) | 45 | 15 | 15 | 15 |
| 2. | Material | 80 | 30 | 30 | 20 |
| 3. | Equipment and services of the third parties | 150 | 50 | 50 | 50 |
| 4. | Commissioning works |  |  |  |  |
| 5. | Scientific and research organizations |  |  |  |  |
| 6. | Software purchase |  |  |  |  |
| 7. | Design/construction |  |  |  |  |
| 8. | Service costs |  |  |  |  |
| **TOTAL:** | | **275** | **95** | **95** | **85** |

## 4.2.  Extra funding sources

**Project (LRIP subproject) Leader / \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

**Proposed timetable and required resources for implementation**

**Project / LRIP subproject**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Items of expenditure** | | | **Cost, k$** | **Expenditure per year(k$)** | | |  |
| 1st year | 2nd year | 3rd year |
|  | | International cooperation | 45 | 15 | 15 | 15 |
| Materials | 80 | 30 | 30 | 20 |
| Equipment, Third-party company services | 150 | 50 | 50 | 50 |
| Commissioning |  |  |  |  |
| R&D contracts with other |  |  |  |  |
| Software purchasing |  |  |  |  |
| Design / construction |  |  |  |  |
| Service costs (planned in case of direct affiliation) |  |  |  |  |
| **Required resources** | **Per hour** | Resources |  |  |  |  |
| * Amount of FTE, | 44,5 | 8,9 | 8,9 | 8,9 |
| * accelerator/installation, |  |  |  |  |
| * reactor,….. |  |  |  |  |
| **Funding sources** | **Budget funds** | Budget of JINR(articles of budget) | 275 | 95 | 95 | 85 |
| **Extra - budgetary** | Contributions of co-executors  Funds under agreements with customers  Other sources funding | 150 | 50 | 50 | 50 |

**Project leader / (LRIP subproject code) \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

**Laboratory Economist \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

**LIST OF APPROVALS OF THE PROJECT / LRIP SUB-PROJECT**

NAME OF THE PROJECT / LRIP SUB-PROJECT

PROJECT SYMBOLS / LRIP SUB-PROJECT

PROJECT CODE / LRIP SUB-PROJECT

THEME CODE / LRIP

NAME OF THE PROJECT LEADER / LRIP SUB-PROJECT

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  | |
| AGREED |  |  |  | |
| VICE-DIRECTOR OF THE INSTITUTE | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF SCIENTIFIC SECRETARY OF THE INSTITUTE | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| DIRECTOR OF THE LABORATORY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF LABORATORY ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| SCIENTIFIC SECRETARY OF THE LABORATORY  THEME LEADER / LRIP | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE  \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME  \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE  \_\_\_\_\_\_\_\_\_  DATE |  |
| PROJECT LEADER / LRIP | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
|  |  |  |  |  |

|  |  |  |  |
| --- | --- | --- | --- |
| APPROVED BY THE PAC FOR THE DIRECTION | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |

**Appendix 4.**

***Project / Subproject Report Form***

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

**1.1. Scientific field**

Particle physics

**1.2. Title of the Project/LRIP**

Astrophysical research in the TAIGA experiment

**1.3. Project code / LRIP**

02-2-1099-2010/

**1.4. Theme code/ LRIP**

02-2-1099-2010/

**1.5.Actual implementation period of the project / LRIP subproject**

2023/

**1.6. Project / LRIP Leader(s)**

A. Borodin, L. Tkachev

**2. Scientific case**

**2.1. Annotation**

Multi-information astronomy is a new direction in modern astrophysics, an important part of which is high-energy gamma-ray astronomy. Gamma rays represent the highest energy part of the electromagnetic spectrum and are a unique tool for studying the most energetic and most extreme processes in the universe. There are a number of fundamental questions for ultra-high-energy (UHE) gamma-ray astronomy that are currently unanswered, and above all, the question of the sources of galactic CRs with energies ~ PeV.

Until now, most of the gamma-ray astronomy data in the TeV and sub-TeV energy ranges have been obtained using the Imaging Atmospheric Cherenkov Telescopes (IACT), in particular, with the stereo systems of several such telescopes. The prototype gamma-ray observatory TAIGA (Tunka advanced instrument or space and gamma-ray astronomy), which is being built in the Tunka Valley, is aimed at energies above 30 TeV. The observatory combines several IACT with a set of relatively cheap Hi-SCORE wide-angle detectors without imaging method (High Sensitivity Cosmic Origin Explorer). This makes it possible to increase the area of the device to several square kilometers and to significantly suppress the background from charged CRs. The combination of two complementary methods of gamma-ray research makes it possible to build a device with a large area at a relatively low cost. TAIGA is the first detector of its kind.

The full scale of the TAIGA observatory is planned to cover an area of 10 km2 and include a network of ~1000 wide-angle (0.6 sr) synchronized Hi-SCORE Cherenkov light detectors, up to 16 IACT with shower image analysis (FOV 10×10 degrees) and muon detectors with a total sensitive area of 2000 m2 distributed over an area of 1 km2. The prototype of the observatory is located in the Tunkinskaya valley - 50 km from Lake Baikal. JINR bears full responsibility for the manufacture of the mechanics of Cherenkov telescopes and composite "faceted" mirrors. In addition, the JINR team participates in shifts during data collection in the Tunka region, MC modeling and physical data analysis.

Over the previous years, the TAIGA-HiSCORE area has increased to 1 km2, deployed three

more IACTs and 200m2 new muon detectors. With such a prototype, you can carry out a scientific

program:

1. Studying the high-energy edge of the spectrum of the brightest galactic and extragalactic sources of gamma radiation

2. Search for galactic PeVatrons.

3. Apply a new hybrid approach to study the mass composition of CR in range 1014-1017 eV.

4. Study of CR anisotropy in the energy range 100 - 3000 TeV.

## 2.2. Extended scientific report

### Introduction

Progress in understanding the nature of high-energy CR sources in our Galaxy and in the Metagalaxy is proceeding along the path of detecting 3 types of astroparticles in experiments: charged CRs, gamma quanta, and neutrinos. For the energy range of gamma rays above 30 TeV, there are a number of fundamental questions that are currently unanswered. First of all, we are talking about sources of Galactic cosmic rays with energies of about 1 PeV, the energy region approximately adjacent to the classical break in the all particle energy spectrum. The study of secondary gamma quanta generated by CRs in the vicinity of the source where particles are accelerated makes it possible to elucidate the mechanism of acceleration of galactic CRs. In the HESS experiments [1. F.Aharonian (HESS Collaboration)//Astroparticle Physics 34(2011) 738-747], VERITAS [2. V.Acciari (VERITAS

Collaboration) Ap. J Letters 730 (2011) L20], MAGIC [3. Albert et al (MAGIC)// Astrophys.J.639:761-765,2006], MILAGRO [4. Abdo AA et al., (Milagro) 2007, ApJ 664, L91], HAWC [5. A. Abdo et al. (Milagro)//arxiV: 1403.0161] sources with gamma-ray spectra extending up to several tens of TeV were discovered. In addition, several measurements of high-energy neutrinos using the IceCube detector point to sources of UHE gamma radiation available for experimental research.

High-energy gamma radiation entering the atmosphere triggers an electromagnetic cascade of secondary e- ,e+ and photons, the Extensive Atmospheric Shower (EAS). Two separate indirect methods measure such EAS. Surface detector arrays measure secondary particles that reach ground level. Such an instrument has a duty cycle close to 100%, as well as a large field of view (FoV). However, their operating parameters, such as energy threshold and resolution, are quite low. On the contrary, IACT measure Cherenkov light produced by secondary charged particles in EAS. IACT observations are mostly limited to good weather and dark nights, resulting in a low ~10% duty cycle. In addition, the IACT field of view is typically only a few degrees across. However, their operating parameters, such as energy and angular resolution and energy threshold, allow for in-depth studies of individual sources.

So far, most of the TeV and sub-TeV gamma-ray astronomy data have been obtained using the IACT, in particular with the stereo systems of several such telescopes. The prototype of the TAIGA observatory [6, N. Budnev et al. (TAIGA Collaboration), Jour.Phys: Conf. Series 718 052006 (2016), 7. Budnev N. et al., (TAIGA Collaboration), NIMA 845, 384 (2017)], which is being built in the Tunka Valley, is aimed at the energy range of gamma rays above 30 TeV. The observatory combines several Cherenkov telescopes with a network of relatively cheap wide-angle (~0.6 sr) TAIGA-HiSCORE non-imaging optical detectors [8 Tluczykont, D. Hampf, D. Horns, L. Kuzmichev et al. Astropart. Phys., 56:42, 2014]. This makes it possible to increase the installation area to several square kilometers and significantly suppress the background from charged CRs due to good gamma-hadron separation of IACT (~100 at energies above 100 TeV). The combination of two complementary gamma separation techniques allows a large area device to be built at a relatively low cost. TAIGA is the first detector of its kind.

The TAIGA observatory's full scale will cover an area of 10 km according to the preliminary plan and include ~1000 TAIGA-HiSCORE detectors, up to 16 Cherenkov telescopes with EAS image analysis (FOV ~10 degrees) and muon detectors with a total sensitive area of 2000 m2, distributed over an area of 1 km2. The advantage of IACT telescopes in combination with the Hi-SCORE array is the ability to use image information about EAS characteristics (axis position, direction, energy) to better separate gamma hadron events. This makes it possible to maintain a suppression level of ~0.01 hadron showers at an energy of 100 TeV even at a distance between telescopes of up to 600 m. Sensitivity of detection of local sources of an observatory with an area of 10 km2 in the energy range of 30–200 TeV, it is expected at the level of 10–13 erg cm–2 s–1 for 500 hours of observation or 10 recorded events, which is comparable to the planned sensitivity of gamma ray astronomy projects (LHAASO [9. G.Di.Sciascio (LHAASO collaboration) //arXiv: 1602.07600], CTA [10. BSAcharya et al. (CTA collaboration) Astroparticle Physics 43 (2013) 3-18;]) in this energy range.

In 2019, the prototype of the TAIGA observatory consisted of 85 HiSCORE stations on an

area of 0.7 km2 and two IACT. During 2020, 30 more HiSCORE stations and a Cherenkov telescope

with an SST-1M camera based on SiPM detectors developed within the CTA project [11 Schioppa EJ et al. [CTA SST-1M Project Collaboration] // arXiv:1508.06453]. This work was not implemented (the

delivery of the camera did not take place). Another IACT was produced and installed in 2021.

TAIGA is the first facility in which telescopes are spaced 300 m or more apart, while retaining the benefits of observing high-energy gamma rays in stereo mode.

With such a TAIGA prototype, it is possible not only to demonstrate the advantages of the hybrid and stereo approach for separating gamma-hadron EAS in the many TeV energy range, but also to obtain new interesting results when studying the high-energy edge of the spectrum of galactic and extragalactic sources. The participation of the JINR group in the TAIGA project was supported by the Russian Science Foundation (RSF) grant No. 19-72-20173 "Small-sized telescopes as part of the experimental complex of the TAIGA gamma-ray observatory" for 2019-2022.

## 2.2.3. Results obtained over the past three years

During the period from 2019 to 2022, during the deployment of the installation, the observation and search for high-energy gamma-ray quanta from 6 sources was carried out: 2 extragalactic ones: Markarian 501 (Mrk501), Mrk421, 2 pulsar nebulae: Crab Nebula, DragonFly Nebula and the remnant the Boomerang G106.3+2.7 supernova, which also contains a pulsar nebula, thought to have originated from the same supernova explosion as the G106.3+2.7 remnant. In all these sources, it was expected to detect high-energy radiation in the region of 100 TeV (except for Mrk421). To date, it has been possible to study the hybrid method (IACT + HiS-CORE) only the Crab Nebula source, since the cones of the HiSCORE stations are directed precisely at this source.

**Energy spectrum of gamma rays from the Crab Nebula according to the first**

**Atmospheric Cherenkov Telescope (ACT)**

The gamma-ray source in the Crab Nebula was observed by the first atmospheric Cherenkov telescope for 150 hours during two seasons (2019-2020 and 2020-2021), 618 events were identified from gamma rays in the energy range of 5-100 TeV. The significance level of such a number of events against the background of charged cosmic rays is 12 sigma (Fig. 2). A technique has been developed for restoring the energy of gamma rays from the data of only one atmospheric telescope. When restoring the particle energy, we used a procedure tuned according to the MC calculations, which leads to**energy determination accuracy of about** 30**%**, and allowing to restore the energy spectrum of events (Fig. 3). The resulting spectrum of particles agrees quite well with world data in the region from 5 to 100 TeV.

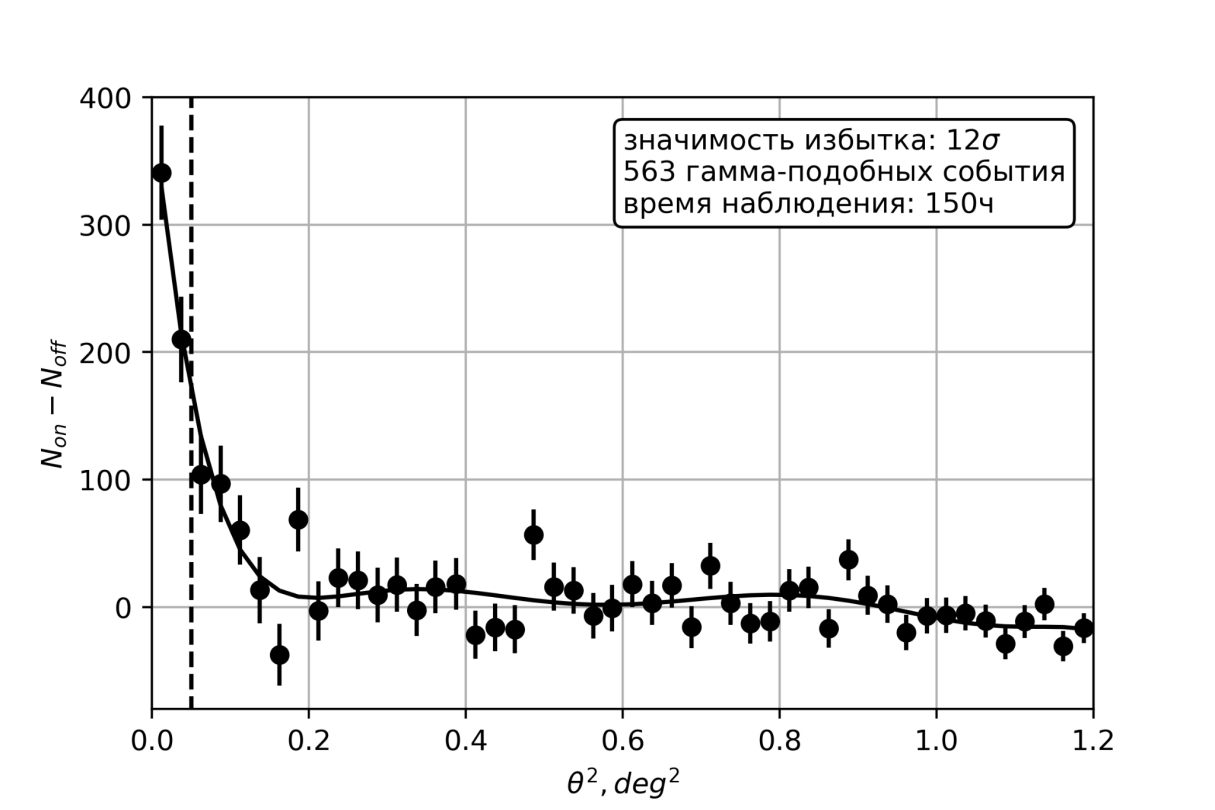


Fig. 2 Distribution by parameter ϴ2 (ϴ- angle between the direction to the source and the direction of arrival of this event)

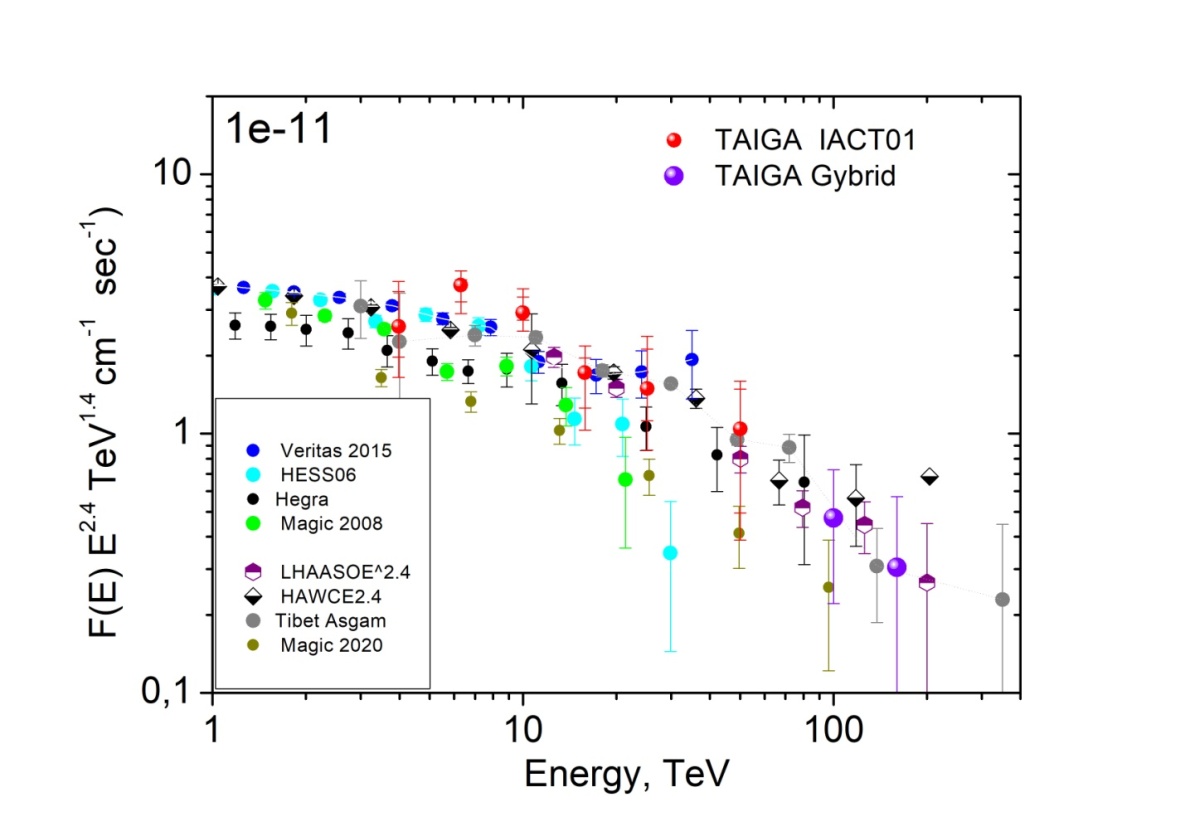


Fig.3. The reconstructed gamma-ray spectrum from the Crab Nebula according to the data of

the first telescope of the TAIGA experiment in comparison with the results of measurements by other observatories over 150 hours of observation. The last two points are based on hybrid events (IACT01+HiSCORE).

### Hybrid events in the observation of the Crab Nebula.

The total statistics of the selected hybrid events for two seasons of observing the "Crab" is

~150,000 (AFT01 + HiSCORE ) for ~ 150 hours. For each event, the Hillas parameters were determined, calculated as two sets of parameters "On" and "Off" for source tracking and background

tracking, and the excess is found after suppression of the hadron background as the difference between these two samples, and the spectra of gamma-like showers are plotted as the difference spectra "On" and "Off.

The analysis of hybrid events additionally includes such parameters as the distance to the

shower axis (Rtel), the angle between the reconstructed EAS direction and the direction to the source, and the energy reconstructed according to the TAIGA-HISCORE setup. Background suppression criteria in hybrid events make it possible to collect events from very large distances - up to 400 m. Therefore, in hybrid events, the effective area turns out to be orders of magnitude larger than when using 1 telescope, the threshold energy for gamma rays turns out to be very high - about 60-80 TeV due to the high energy threshold of registration of TAIGA-HiSCORE stations. The analysis used data from only a quarter of the installation, with an area of 0.25 km2. For 150 hours, 6 gamma quanta were emitted with energies above 100 TeV (Fig. 3). Thus, according to the data of the entire TAIGA-HiSCORE facility and 3 telescopes, **20-30 events with energies above 100 TeV can be expected from the Crab Nebula in 150 hours of observation.**

### Spectrum of gamma rays from the Crab Nebula in stereo

Stereo observations of the Crab Nebula were carried out by the first two telescopes of the TAIGA-IACT installation from October to February of the 2020-21 season. The analysis implies the standard calculation of the Hillas parameters for each event (relative to 7 background positions and one source), as well as the calculation of additional parameters required for stereoscopic reconstruction of the EAS geometry. For 36 hours of observation, a signal with a significance at the level of 5σ was obtained and the energy spectrum (Fig. 4), which is in good agreement with the data from the HAWC and TIBET AS+MD high mountain arrays.

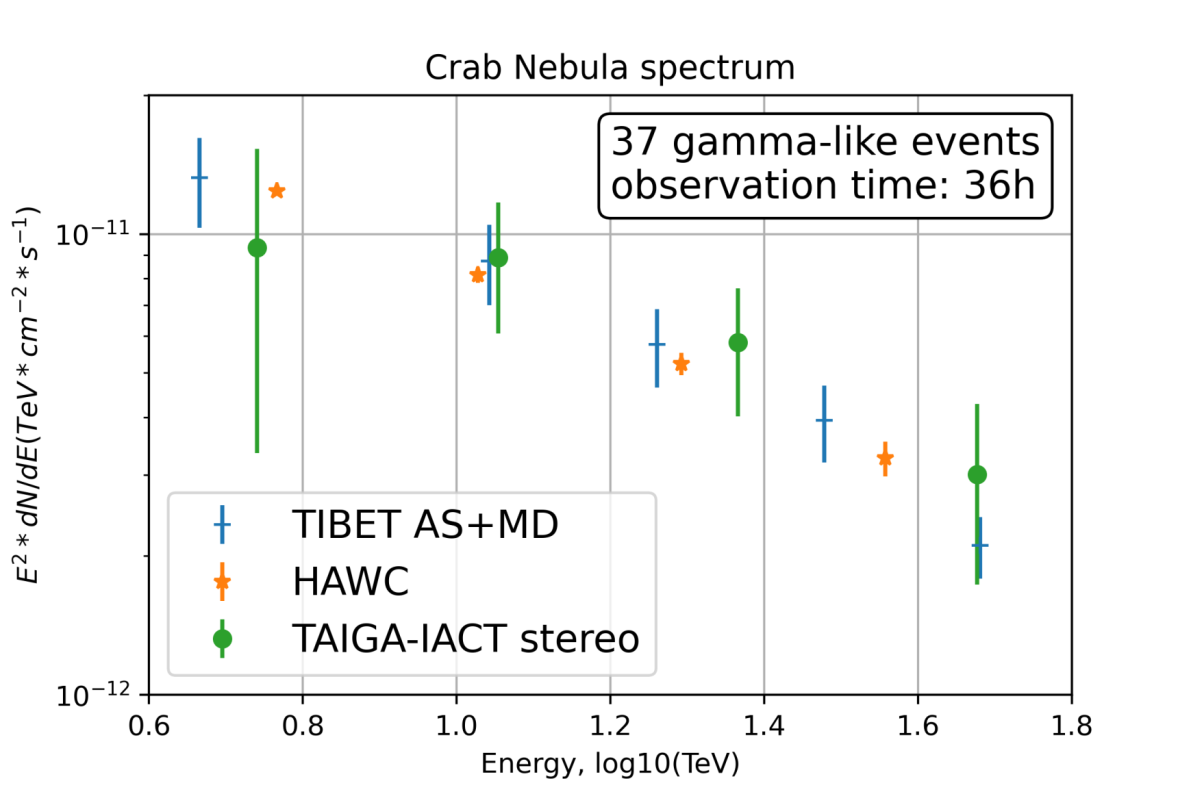


Рис.4 The energy spectrum of gamma quanta, reconstructed by the stereo method.

### Gamma rays from blazars Mrk421 and Mrk501

The first extragalactic source Mrk421, from which a signal was detected in the TAIGA experiment, is a blazar located near the Earth (redshift z~0.03) with variable intensity, well measured in TeV radiation, but high-energy events over 20 TeV were not expected. The exposition of Mrk421 in the Tunka Valley in the 2019-2020 season was 62 hours from November to the end of February with good weather. On Fig. 2 shows the alpha distribution for 'On' events and for 'Off' events with step 4o selected according to optimal criteria

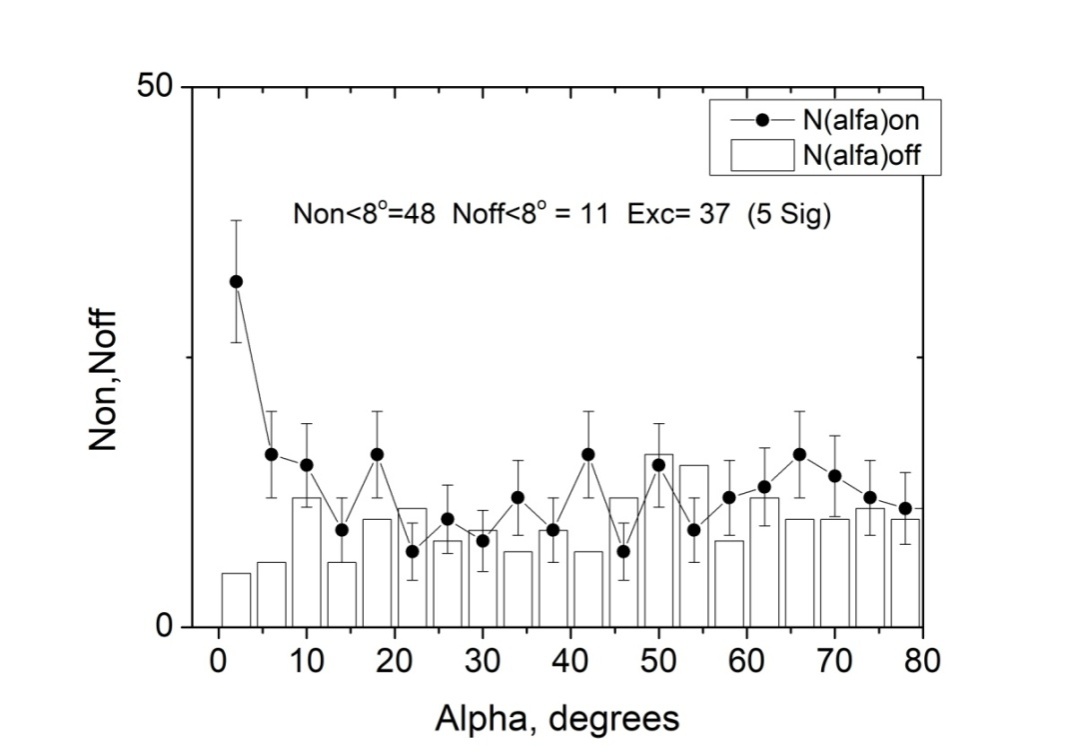


Fig. 5 Distribbution by parameter α ‘On’ and for ‘Off’ events from blazar Мrk421, отобранных selected according to the following criteria: Size>172 ph. e.; dist= 0.5o -1.25o, 0.024o<Width<0.068o× lgSize-0.045o, Length<0.31o,Con2>0.44.

In the region α<10, 37 showers with a significance of 5.77σ were registered, and in the region α<6oExc=141 events with a significance of about 5σ, at a threshold energy of about 3 TeV. The observation was carried out according to the IACT01 work.

The Blazar Mrk 501 is located at a distance from the Earth with a redshift of z=0.034. To date, the data for 2019-2020 from March to May have been processed and analyzed. The total observation time during this period was ~ 27 hours. To identify gamma-like showers, we used an approach tested on the registration of radiation from the Crab Nebula. The excess is about 30 events. But the significance is not high - about 2.5 sigma.

### Pulsar Dragonfly Nebula

This is a pulsar nebula in the region of the well-known constellation Cygnus, in which the process of star formation is underway. The nebula was created and is fueled by the rotational energy of the pulsar PSR J2021+3651. It is characterized by high-energy TeV radiation, previously detected by VERITAS and HAWC: in the 10 TeV region, the radiation intensity is comparable to the Crab radiation, but decreases exponentially at energies above 37 TeV, although events in the 100 TeV region are also observed. Therefore, this source is considered as one of the most promising. The processing of the data from this source was carried out in stereo mode. Total observation hours 40. In total, 144 ON-events and 100 OFF-events were registered for two samples with different angles, the excess was 44 events, and taking into account the choice of 5 background points, this corresponds to a significance of 3.37sigma.

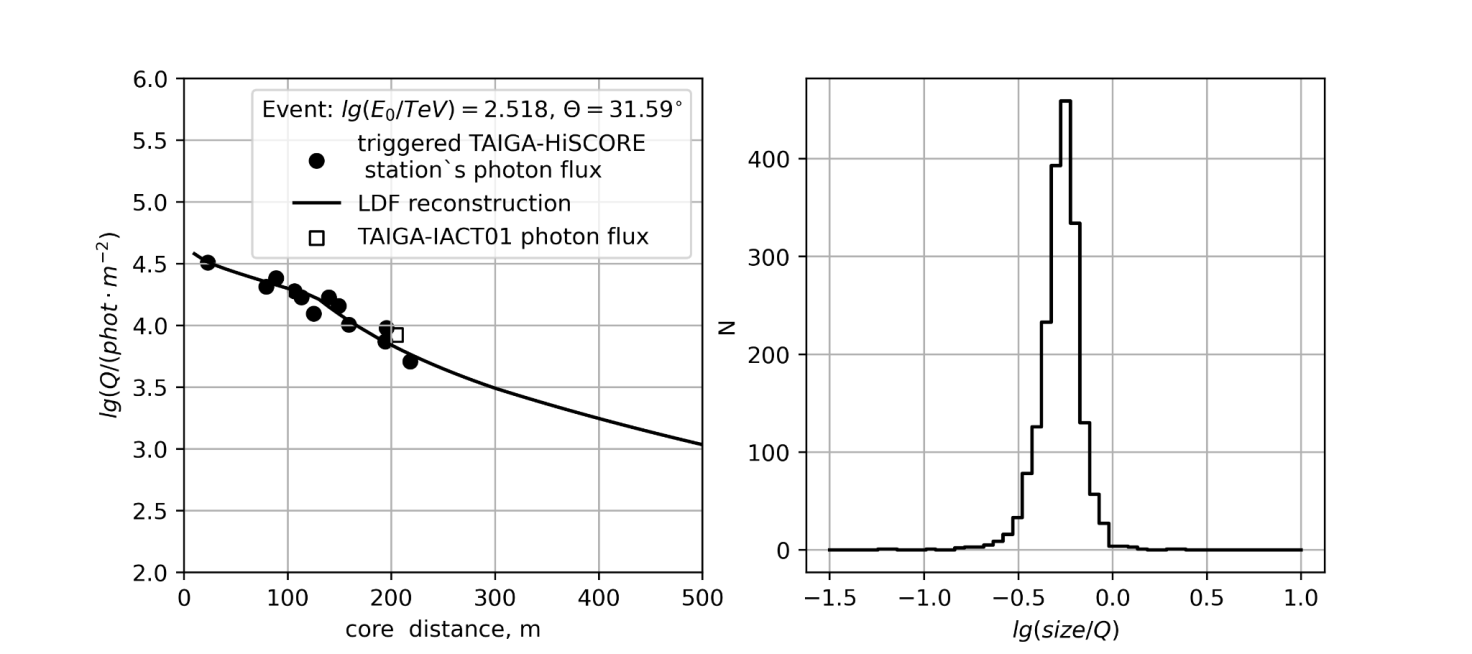
**Search for high-energy gamma-rays from the Boomerang source**

During the 3 observation seasons of 2019-2022, about 140 hours of observation of the source for IACT01 and about 100 hours for IACT02 were collected. From an astrophysical point of view, this is a very interesting source. The pulsar nebula associated with pulsar J2229+6114 and the supernova remnant (SNR) G106.3+2.7 are thought to be the result of the same supernova explosion, since the whole structure is located on the edge of a bubble with extended regions of molecular gas inside and about 800 ps, and the supernova explosion occurred in the region of active star formation. From an experimental point of view, its spectrum, measured in the Milagro and HAWC experiments, is of interest; the measured intensity in the region of 100 TeV is comparable to the intensity from the Crab Nebula. However, in the region of about 5-10 TeV it is an order of magnitude lower.

### Monte-Carlo calculations of the telescope response and their experimental calibration

In the TAIGA experiment, EAS modeling is performed using the CORSIKA version 7.35 package with the QGSJET-II-04 model for high-energy interactions and GHEISHA-2002d for low-energy interactions. Details and references can be found in reference [16]. A set of image parameters was determined that made it possible to most effectively suppress the background and register gamma quanta. One of the most important parameters for reconstructing the EAS energy is the coefficient of transition from the number of photoelectrons in the image size to the photon flux I(phot/m2) falling on the telescope mirrors, R= size/I. In Monte Carlo calculations, estimates of this coefficient (RMK) are associated with a number of uncertainties (reflection of light from mirrors, allowance for the passage of light through the entrance window of the camera, reflection of light from Winston cones, quantum sensitivity of photomultipliers, etc.), therefore, an independent estimate of this value is required. In the TAIGA experiment, the ratio of size to the photon flux (Rexp) was obtained from hybrid events recorded by the telescope and HiSCORE stations. For such events, the energy E, reconstructed from the photon density at a distance of 200 m from the EAS axis, and the photon spatial distribution function (PDF) reconstructed from the data of the HiSCORE stations are known with an accuracy of about 10% [17].

Using the PDF, one can obtain the number of photons at the telescope position I, compare with the number of photoelectrons in the image recorded by the telescope, and obtain the value of the ratio Rexp= size/ I. The coefficient obtained from the event bank turned out to be equal to Rexp= 0.56 ±0.03 + 0.07syst. In Monte Carlo calculations RM-K=0.63 pe +/- 0.03, which agrees with the experimental value within the error and confirms the correctness of the performed simulation. An example of a hybrid event is shown in fig. 6 A. Black dots are the experimentally measured PDFs for the Hi-SCORE stations, the solid line is an approximation of this PDF, a square is the light flux at the point where the telescope is located. R distributionexp shown in fig. 6 B.



|  |  |
| --- | --- |
| А | Б |

Fig.6. A: An example of a hybrid event. The black circles are the experimental points of the

PDF for the HiSCORE stations, the solid curve is an approximation of this PDF, the black square is the light flux at the telescope location, recalculated from the event recorded by the telescope with the coefficient Rm-k=0.63. B Distribution by coefficient Rexp

## 3. Program for the development of the astrophysical complex

The immediate development of the TAIGA astronomical complex is associated with the creation of two more atmospheric Cherenkov telescopes and a significant increase in the area of muon

detectors (TAIGA-MUON facility). One of the shortcomings of the hybrid approach in the existing version of the astrophysical complex is the significant difference between the angular aperture of the Cherenkov telescopes and the aperture of the TAIGA-HiSCORE facility, leading to the possibility of observing only one source at a given time. To correct this situation, it is planned to create small imaging Cherenkov telescopes (SIT) with an angular aperture of 25-30 degrees and an energy threshold of 80-100 TeV. The joint operation of such telescopes and the TAIGA-HiSCORE facility will increase the number of hybrid events by almost 10 times, for which gamma rays can be extracted against the background of cosmic ray events. Further development of the astrophysical complex, most likely elsewhere, is associated with the expansion of the TAIGA Hi-SCORE facility to an area 10 times larger and supplemented by small imaging Cherenkov telescopes.

### Cherenkov telescopes

The mechanical part of the fourth Cherenkov telescope was manufactured at JINR, shipped and assembled at the test site (Fig. 7). Three telescopes are operating as planned. Planned work is underway to manufacture the upgraded fifth telescope.



Fig. 7 The first, fourth and third telescopes at the test site in the Tunka Valley.

### Wide-angle telescope

As part of the work on promising areas to expand the TAIGA project, JINR participated in the discussion of modeling and manufacturing a prototype of a wide-field Cherenkov telescope. The use of such telescopes in conjunction with distributed detectors will make it possible to obtain large statistics of joint events in the high-energy region due to the large field of view of the telescope. The parameters of the telescope prototype are presented in Table 1.

Table 1.

|  |  |
| --- | --- |
|  | Value |
| **Lens** |  |
| Lens diameter, mm | 820 |
| Focal length, mm | 3666±100 |
| Maximum field of view, degrees | ±7,5 |
| Maximum field of view, mm | 940 |
| The siz of the field of view used, mm | 600 |
| Telescope positions, ° from vertical (telescope oriented to the South) | 0, 35, 90 |
| **Camera** |  |
| FOV of one pixel | ~ 0.4 ° |
| Number of pixels | 1000 - 1200 |

It can be noted that such a telescope will work together with HiSCORE stations, the energy threshold of which is about 70 TeV. Thus, it can be seen that in the region of joint work energies, the effective area covers dozens of stations and can help the EAS analysis by having a spatial pattern in several pixels.

A prototype of a wide-angle lens Cherenkov telescope has been successfully manufactured and installed at the test site. At present, the camera is expected to be manufactured and the telescope can start working.

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Published in: Nucl.Instrum.Meth.A 1039 (2022) 167047 • Contribution to: VCI2022

4. TAIGA - an advanced hybrid detector complex for astroparticle physics and high energy gamma-ray astronomy

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TAIGA Collaboration : I. Astapov(Moscow Phys. Eng. Inst.) et al. (May 16, 2022)

Published in: JINST 17 (2022) 05, P05023

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