Strategy for Long Range Program in Neutrino Physics

Executive Summary:

Neutrino Physics plays a key role in understanding the laws governing the Universe. Nowadays, the significance of Neutrino Physics is steadily increasing since it has entered its precision era.

JINR, due to the explorations led by B.Pontecorvo since 1950s, developed a strong and influential neutrino school with about 100 researchers working in this field today. JINR leads the world's largest **Neutrino Program** <u>covering experimentally all sources of neutrinos</u>, accompanied by strong theoretical investigations and sophisticated data analysis. The JINR management intends to fully support the Neutrino Program for strengthening the research by the JINR scientists in advanced experiments and further developing the competence and know-how.

Together with INR (Moscow), JINR plays already a leading role in the construction, data taking, reconstruction, calibration and data analysis of **Baikal GVD (Gigaton Volume Detector)** with an aim to build a 0.4km^3 detector by 2021 and 1.5 km^3 detector by 2027. JINR invests about **5M USD** per year to accomplish these goals. In 2019, Baikal GVD is the largest neutrino telescope in the northern hemisphere with its ¼ km^3 detector. The **TAIGA** installation - a set of gamma and muon telescopes hosted in Siberia, in Tunka Valley, to the south of Lake Baikal, can be regarded as a supplemental instrument in terms of multi-messenger astronomy. Together, Baikal-GVD and TAIGA might form a unique multi-messenger observation tool for events occurring in the Universe integrated into the global international network. These days, exciting observations of great activities on Betelgeuse demand well-orchestrated and simultaneous observations of gamma and neutrinos to be ready if and when Betelgeuse turns into a supernova. This direction of research is of great importance and will be seriously considered by the JINR management for strengthening its gamma-rays counterparts.

The scientific program with several research directions to be carried out at JINR in Neutrino Physics and Astrophysics is presented in this report for the mid-term (2024-2030) and long-term (2031-2037) periods.

The main directions of research in neutrino physics for the medium and long terms are related to:

- Observation of neutrino interactions from neutrinos from accelerator-based sources, from nuclear reactors and from cosmic sources. with very large and sophisticated instruments
- Studies for further insight in the evolution of the Universe through astrophysical and cosmological observations boosted by the development of new instruments, like gravitational wave detectors (a new channel for Multi-Messenger Astronomy), as well as through searches for dark matter and dark sectors at colliders and in non-accelerator experiments.

As a long-term program, JINR may consider building its own gravitational wave detector in Russia, which will enormously boost GW astronomy in Russia and the JINR member-states. The flat large area around Dubna was already positively evaluated for the large system of the ILC and can serve extremely cost-effectively to such a GW Laser system

Introduction

Neutrino Physics

Neutrino Physics is of great value to our comprehension of the laws reigning over the Universe. Nowadays, the significance of Neutrino Physics is steadily increasing since its precision era has already started.

Due to the explorations headed by Bruno Pontecorvo since the 1950s, JINR developed a strong and influential neutrino school with about 100 researchers working in this field today. JINR leads the world's largest **Neutrino Program** covering all sources of neutrinos, assisted by strong theoretical investigations and detailed data analysis. JINR plans for a full support of the Neutrino Program encouraging the participation of its scientists in advanced experiments for keeping up their research competence, and the know-how gained so far.

Cosmic neutrinos:

JINR plays, along with INR (Moscow), a leading role in the construction, data taking, reconstruction, calibration and data analysis of the **Baikal Gigaton Volume Detector** (**Baikal-GVD**) with an aim to build a 0.4km^3 detector by 2021 and a 1.1-1.2 km^3 detector by 2027. JINR invests about **6M USD** per year to accomplish these goals. In 2019, Baikal-GVD is still the largest neutrino telescope in the Northern Hemisphere with its ¼ km^3 detector.

JINR is about to strengthen further its leading position by substantially increasing efforts in data analysis to yield the highest quality scientific results in the observation of ultra-high astrophysical neutrinos and related studies. Furthermore, any attempts to perform profound limnological and environmental explorations of Lake Baikal are welcomed by JINR. The perspectives of Baikal-GVD are well defined for the medium and long term and described in more detail below.

Neutrinos from nuclear reactors:

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine neutrino mass hierarchy and precisely measure oscillation parameters. It detects reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants, observes supernova neutrinos, thus allowing studies of atmospheric, solar neutrinos and geo-neutrinos, and of exotic searches, with a 20-thousand-ton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) at 700-meter deep underground.

The major motivation for **JUNO,** the reactor antineutrino experiment, is the determination of the neutrino mass ordering at 3-4 standard deviations confidence level. JINR is a key JUNO collaborator with well visible financial and intellectual contributions. JINR also has a clear research program outlined below. The JINR group is to broaden its role in the software development and data analysis for the long-term period.

Neutrinos from Accelerator based sources:

The next breakthrough in the determination of the neutrino mass ordering and CP-violation in the lepton sector can be expected from a global analysis of neutrino data and from precision measurements at accelerator long-baseline experiments. **Deep Underground Neutrino Experiment** (**DUNE**) is an experiment under construction, with a near detector at Fermilab and a far detector at the Sanford Underground Research Facility that will observe neutrinos produced at Fermilab. **HyperKamiokande** in Japan is to observe neutrinos also from the accelerator at J-PARC in Japan. The **NOvA** (NuMI Off-axis ν_e Appearance) experiment uses two detectors: a 300 metric-ton near detector at Fermilab and a much larger 14 metric-kiloton far detector in Minnesota just south of the U.S.-Canada border.

JINR, presently successfully participating in the NOvA experiment, is considering joining at least one of these experiments. The decision should be taken based on a) the accuracy of their measurements, which-however- are presently expected to be comparable to each other, and b) on the size of the requested JINR contribution which needs to be big enough for a leading laboratory in the collaboration.

Multi-Messenger Astronomy Including Gravitational Wave Detection

It is understood nowadays that different observations of the same phenomenon occurring in the Universe via different signal detection systems could give a further insight into the evolution of the Universe. Such an observation of one single phenomenon via several different signals is called multi-messengers' astronomy. These days, exciting observations of great activities on Betelgeuse demand well-orchestrated and simultaneous observations of gamma and neutrinos to be ready if and when Betelgeuse turns into a supernova. Multi-messengers' astronomy is absolutely needed to exploit such a rare event, especially so close to Earth.

Baikal-GVD mentioned above is one of the cornerstones of this approach. The **TAIGA** installation - a set of gamma and muon telescopes hosted in Siberia, in Tunka Valley, to the south of Lake Baikal, can be regarded as a supplementing instrument in terms of multi-messenger astronomy. Together, **Baikal-GVD** and **TAIGA** might form a unique multi-messenger observation tool for events occurring in the Universe. This direction of research being of potentially great importance is seriously considered by the JINR management towards the strengthening of its gamma-rays counterpart. **TAIGA** is planned to be set up as a truly international collaboration, achieving the world level quality standards in the technologies, commissioning, software and data analysis. JINR will take all necessary steps for attracting world-class experts to lead this project.

The recent discovery of gravitational waves is one of the most remarkable discoveries ever, which opened a new window to observe the Universe. Russia currently lacks any gravitational wave detector and this disparity must be removed. JINR proposes to enter this field of research, which requires developing new expertise in many fields ranging from General Relativity to precision laser interferometry. It should be noted that JINR has already made the first step forward in this direction having installed its brand-new laser inclinometer at the VIRGO detector (see Sec. 2.3). In the medium term, JINR plans to develop a necessary expertise missing by now and prepare itself for the competent collaboration at the existing gravitational wave detectors like **LIGO, VIRGO**, **KAGRA** and/or at the third-generation detector **Einstein**.

In the medium to long-term period, JINR will consider plans to build its own gravitational wave detector in Russia which will enormously boost GW Astronomy in Russia and in JINR's Member States as well.

Short Summary of Past Research Projects

In this section we will briefly review the most remarkable results in Neutrino Physics and Astrophysics achieved with a decisive contribution of the JINR scientists over the last seven years. These attainments are to be considered separately in Physics and technologies. Below we will summarize all the JINR contributions in this field.

Discoveries in Physics.

1. **Discovery of a non-zero value of the lepton mixing angle θ_{13} and of the third mode of neutrino oscillation. The most precise measurement of this parameter.** This discovery was done in the Daya Bay experiment [1], [2].
2. **Discovery of the muon neutrino oscillation to a tau neutrino.** This observation at five standard deviations confidence level was done in the OPERA experiment [3], [4], [5].
3. **Geo-Neutrinos.** Anti-neutrinos produced by the crust and mantle of the Earth were first discovered in the BOREXINO [6] and KamLAND [7] experiments.
4. **The first spectroscopic measurement of pp and 7Be solar neutrinos and the first observation of matter effect in neutrino oscillation.** These observations were performed within the BOREXINO experiment [8].

JINR's contributions to the above-mentioned discoveries are briefly summarized in some details below.

Daya Bay Experiment.

- Production and commissioning of the wavelength shifter PPO for the liquid scintillator of the Daya Bay detectors.
- Data analyses. In particular, the results of the data analysis 2016 [9] were based on the analysis performed by JINR.
- The JINR scientists were awarded **"The Breakthrough Prize in Fundamental Physics 2016"** as members of the Daya Bay Collaboration.

BOREXINO Experiment.

- Commissioning of CTF (BOREXINO prototype) and of the BOREXINO photo-multipliers (tests, cabling, mounting, cleaning, calibration, software).
- Leading analyses of solar and geo-neutrinos, and searches for non-standard interactions.

OPERA Experiment.

- The JINR team, along with a French group from Strasbourg, created the main tracking detector - the Target Tracker - which provided the neutrino interaction position in the setup. Since the beginning of the experiment, JINR took a **leading role** in the Target Tracker data analysis.
- The software algorithms developed at JINR allowed efficient location of the neutrino interaction vertex in the OPERA emulsion target brick - an important step without which the tau neutrino search would have been impossible.
- JINR participated in the emulsion analysis having created the dedicated nuclear emulsion scanning facility equipped with two up-to-date automatic microscopes.
- Many OPERA results were published with an active participation of the JINR team as editors or internal referees, and also reported many times within major international conferences.

Technological Breakthroughs.

1. **Construction of a ¼ cubic kilometer Baikal Neutrino Telescope.** The Baikal-GVD collaboration, led by both the JINR and INR scientists, has started the construction of the neutrino telescope of a cubic kilometer size in Lake Baikal. By now, the assembled facility is already considered to be the largest in the Northern Hemisphere.
2. **Breakthrough in the reading speed from nuclear emulsion.** Researchers from the OPERA collaboration managed to increase the speed of nuclear emulsion processing by a factor of one thousand, now reaching the record 5000 cm^2 per hour. This advancement opened new possibilities for studies of short-lived particles in the DsTau and FASER experiments at CERN, tau neutrinos in SHiP at CERN, searches for dark matter in NEWS-

dm at Gran-Sasso. This technology is used also in applied research such as cosmic-ray muon radiography of volcanoes, archeology and geoscience. Lead by scientists from Nagoya (Japan) and Napoli (Italy), the JINR physicists contributed to this research in the development of software and emulsion processing, a part of which was carried out at the DLNP scanning facility. The first tau neutrino observed by the OPERA experiment is depicted in Fig.1.

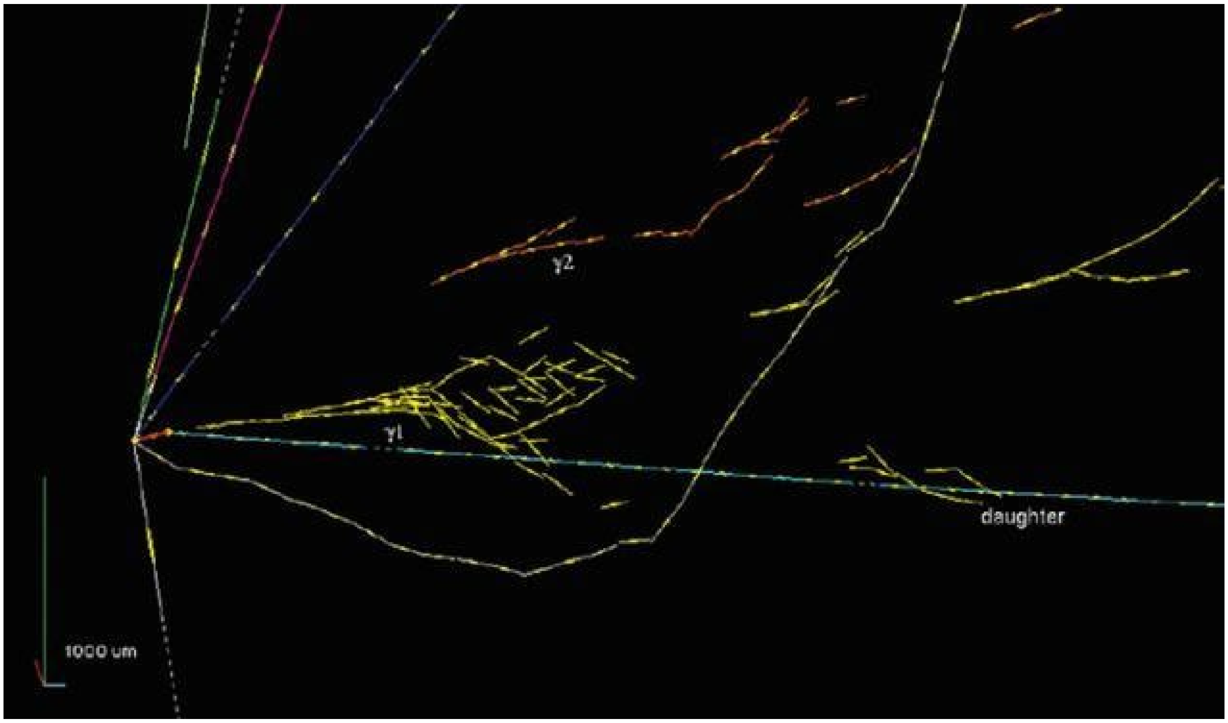

Fig. 1 The first tau neutrino interaction observed in the OPERA nuclear emulsion. The tau lepton track can be seen as a short red line connecting two displaced vertices. The tau lepton decayed presumably into a rho-minus meson and a tau neutrino. The rho-minus meson subsequently decayed into pi-minus (a long track labeled as "daughter") and pi-zero mesons. The latter almost immediately decayed into two photons which both produced electromagnetic showers labeled as $\gamma 1$ and $\gamma 2$.

Image credit: the OPERA collaboration.

Short Summary of Present Research Projects

The DLNP scientists participate in a number of home and international experiments in Neutrino Physics and Astrophysics.

The unique feature of DLNP is its Neutrino Program - the world's largest one. It includes the following experiments.

1. **Baikal-GVD.** In total, 25 FTE work in this experiment on its construction, calibration, data taking and data analysis.
2. **Daya Bay.** In total, 8 FTE work in this experiment on data analyses.
3. **JUNO.** In total, 22 FTE work in this experiment on design, production and commissioning of high-voltage units for 20 thousands of 20'' PMTs and for 25 thousands of 3'' PMTs; commissioning of the TopTracker detector; PMT tests and their characterization by the

JINR PMT scanning stations; Muon track reconstruction code development; Development of the Global Neutrino Analysis (GNA) software.

4. **NOvA.** In total, 14 FTE work in this experiment on hardware and software development; data taking and analysis.
5. **BOREXINO.** In total, 4 FTE work in this experiment on data analyses.
6. **DANSS.** In total, 10.5 FTE work in this experiment on its construction, calibration, data taking and data analysis.
7. **GERDA.** In total, 5.4 FTE work in this experiment on development of germanium semiconductor detectors and data taking.
8. **GEMMA-III and νGEN.** In total, 10 FTE work in this experiment on development of germanium semiconductor detectors, data taking and data analysis.
9. **SuperNEMO.** In total, 5 FTE work in this experiment on data taking and data analysis.
10. **EDELWEISS.** In total, 9 FTE work in this experiment on data taking and data analysis.
11. **TAIGA.** In total, 11.2 FTE work in this experiment on detector construction, data taking.

National and International Networking Context

The overwhelming majority of the JINR scientific research activities in Neutrino Physics and Astrophysics is embedded into the international context due to the very nature of the structure of the modern astroparticle community and special features of data taking in international collaborations. JINR systematically invests resources in the development of both the national research infrastructure and experimental facilities, allowing present and future generations to work in the top-ranked scientific surroundings.

Staff and Equipment

DLNP

Nowadays, the DLNP scientists run a wide range of experimental projects both at home and elsewhere. There is a variety of unique competences accumulated in methodology, detector construction, data analyses.

The scientific program of DLNP includes Particle Physics, accelerator technologies, Neutrino Physics and Astrophysics, Radiation Medicine, Genetics and molecular genetics studies, Radiochemistry and Nuclear Spectroscopy, ultra-cold temperatures as major directions.

From the 727 employees of DLNP, **278** are scientists, **304** are engineers and specialists, **121** are technicians and **24** are from administration. **39** of the scientists have a degree “Doctor of Science”, while **141** have a degree “PhD”.

DLNP has its own Information Technology Division, responsible for computer resources, data storage, internet access and lots of various services, and an Engineering Design Department with about two dozen highly qualified engineers.

The laboratory is equipped with several dozens of machines, including modern numerical CNC machines (SafanDarley, HAAS), 3D-printers and scanners. There is also a proton synchrophasotron, a linear electron accelerator, radiochemical equipment, microelectronics for R&D and production lines, as well as various tools and instruments for R&D of particle detectors.

Expertise to Be Developed

JINR is determined to develop these currently missing expertises for achieving the research goals presented in this report:

- Application Specific Integrated Circuit (ASIC).
- FPGA Electronics.

- Robotics.
- Quantum Computing.
- General Relativity and Gravitational Interferometry.
- Project management.

BAIKAL-GVD

Motivation

The major motivation for the **Baikal-GVD** cubic-kilometer neutrino-telescope is related to an unambiguous identification of sources of neutrinos with ultra-high energy (UHE) belonging to PeV energy range. An identification of such sources could give us a new knowledge and deeper insights on the Universe evolution, formation of galaxies and black holes, on natural accelerators of particles, boosting them to extreme energies and related phenomena.

Fig.2 Five clusters of Baikal-GVD neutrino telescope installed by 2019.

The Baikal-GVD experiment-presently under construction will be a multipurpose research facility, intended to deliver data with unprecedented precision in neutrino physics and to make important contributions to dark matter searches, cosmic ray physics and limnology.

Five clusters installed by 2019 made Baikal-GVD the largest Neutrino Telescope in the Northern Hemisphere. A schematic view of five clusters is shown in Fig.2.

The **Baikal-GVD** experiment is expected to play a leading role in the multi-messenger astronomy determining the world-wide activity together with other neutrino and gamma-telescopes and with gravitational wave detectors. An identification of UHE neutrino sources is expected making a breakthrough in our understanding of the Universe evolution, galaxy formation, providing further tests of the theory of general relativity, and giving insights on natural particle accelerators. The Baikal Neutrino Telescope will be also unique as a precision monitor of the Baikal Lake, sensitive to tiny variation of its water properties, thus providing a great new tool for limnology.

Baikal Neutrino Telescope will be a unique laboratory on the territory of Russia providing great opportunities for scientific research to new generations.

Depending on the results obtained by the end of the mid-term period, a decision to increase further the fiducial volume might be taken at that time. One can foresee in an optimistic scenario that an increase of the volume by a factor of two will make a precision neutrino astronomy possible.

The Baikal GVD experiment is considered being a flagship INR and JINR experiment.

International Context

The Baikal GVD construction, data taking and analysis, under leadership of INR (Russian Academy of Science) and JINR, is considered as a "home" experiment with its installation on the territory of Russia.

A number of institutions from Russia and JINR-member-states (Czech Republic, Slovakia, Poland) joined the experiment making important contributions. Further internationalization of the project is expected.

Proposed Research

There are three phases of construction of Baikal GVD project considered:

1. Phase I. By 2021, 0.45 km^3 detector should be constructed, which would correspond to the actual fiducial volume of the IceCube detector.
2. Phase II. By 2027, the detector should increase up to 1.2 km^3 volume.
3. Phase III. By 2037, the detector should increase up to 2.4 km^3 volume.

The proposed research for the mid-term reads:

- R&D for the new electronics, fully digital trigger and optical links for the data transfer.
- Construction of the phase II detector.
- Development of algorithms for the track-reconstruction, particles energy and direction reconstruction, identification of neutrino flavour.
- Development of multi-messenger alert system and integration into the world-wide multi-messenger network.
- Accurate measurement of atmospheric muon and neutrino fluxes.
- Data analysis and search for UHE neutrinos.
- Search for UHE neutrino sources.
- Search for magnetic monopoles and dark matter particles.

The proposed research for the long-term reads:

- Multi-messenger astronomy within the world-wide multi-messenger network.
- Precision measurement of atmospheric muon and neutrino fluxes.

- Identification of UHE neutrino sources.
- Search for magnetic monopoles and dark matter particles.

Required Resources

- R&D and Phase II detector installation require about **45M** USD for the mid-term period.
- R&D and Phase III detector installation require about **90M** USD for the long-term period.

JUNO

Motivation

JUNO is a multipurpose experiment studying reactor antineutrinos. JUNO detector is shown in Fig.3.

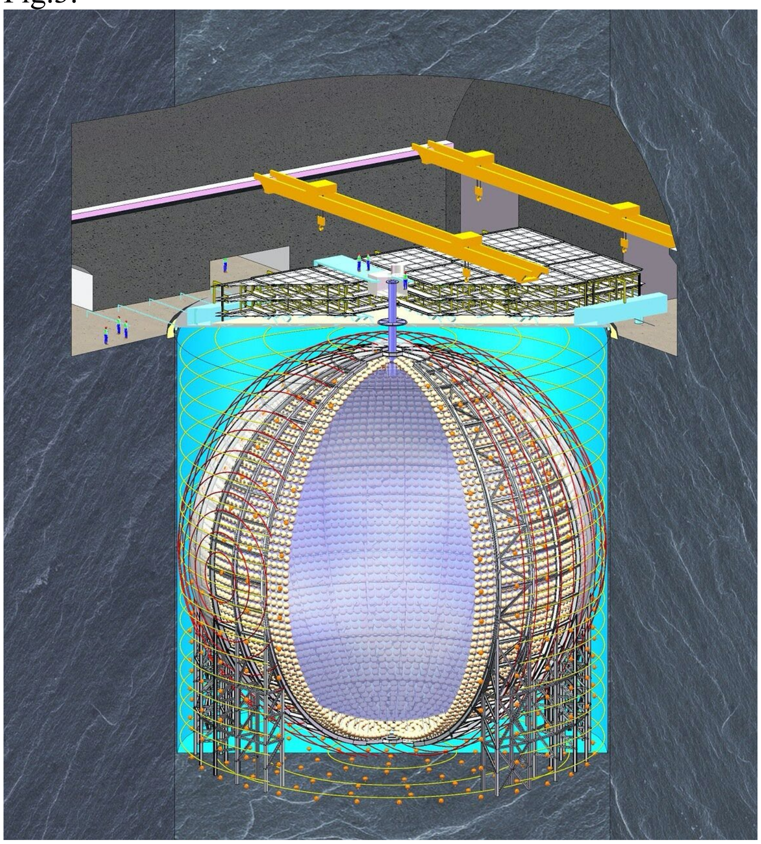

Fig.3 Schematic view of JUNO central detector. The diameter of the sphere, filled with 20 thousand tons of liquid scintillator and surrounded by about 20 thousand 20’’ PMTs and 25 thousands of 3’’ PMTs, is about 40 meters. Image credit: JUNO Collaboration.

The major physics program includes

- Determination of neutrino mass ordering at confidence level of 3-4 standard deviations, as the main scientific goal of JUNO experiment.
- Determination of lepton mixing angles and neutrino mass splitting with an accuracy better than 1% in a single experiment. This precision will be comparable to that in the quark sector.

- Observation of SuperNova (SN) neutrinos with an unprecedented statistics and details. If SN explosion happened at a distance of about 10 kpc, JUNO would observe about ten thousand of SN neutrinos. Such an observation enables testing of the SN models and independently determining the neutrino mass ordering.
- Observation of diffuse SN neutrinos. 1-4 neutrinos/year. If measured it would be a discovery.
- Geoneutrinos detection. JUNO will observe up to 40 times larger statistics of geoneutrinos than the present world dataset.
- Solar neutrino detection.
- Atmospheric neutrino detection.
- Proton decay to kaon and neutrino.
- Potential upgrade of JUNO to search for $0\nu\beta\beta$ with the world record sensitivity.

International Context

JUNO experiment consolidates effort of a large international community from China, Russia, Europe, South America. The total number of collaboration members is close to 700. JINR plays a major role in the experiment both financially and intellectually.

The common work towards the construction of the 1st multi-kiloton liquid scintillator detector will be more effective and will help in the formation of the new generation of scientists in the international environment.

Scientists from JINR-member states Armenia, Slovakia, Czech Republic are involved in JUNO experiment.

Proposed Research for the mid-term:

1. Development of Global Neutrino Analysis (GNA) fitter and determination of neutrino mass ordering.
2. Determination of lepton mixing angles and neutrino mass splitting.
3. Analysis of geoneutrinos.
4. Analysis of solar neutrinos.

Proposed Research for the long-term:

1. Precision measurement of neutrino mass ordering and lepton mixing angles.
2. Probe the unitarity of lepton mixing matrix.
3. Precision measurement of geoneutrinos signal.
4. Analysis of solar neutrinos.
5. Search for proton decay.
6. Search for neutrinoless double beta decay.

Required Resources

At the phase of R&D and detector construction JINR invested in total about **6M USD** as its hardware contribution to the project. These include

- **2M USD for HV units.** Design, production and commissioning of high-voltage units for 20 thousand of 20 inches photo-multipliers and for 25 thousand of 3 inches photo-multipliers.
- **1M USD for TopTracker.** This includes 0.8M USD as in-kind contribution and 0.2M USD for TopTracker support system.
- **2M USD for JUNO Computing Farm.** JINR will be one of three European centers for data storage, Monte-Carlo Production and Reconstruction Processing of JUNO.
- **1M USD for a purchase of SiPM for Taishan Antineutrino Observatory (TAO).** TAO main objective is a record measurement of nuclear reactor spectrum with a precision of 2%.

The resources needed for **2023-2030** for operation phase are estimated as **7.5M USD** in total. The breakdown:
Hardware contribution to the construction of the 1st multi-kilo-ton liquid scintillator detector: Equipment: done.

a) Small scale R&D: **0.7M** USD.
b) Team expenses on site: **0.4M** USD.

Manpower FTEs: 22

- Travel expenses: **1.4M** USD.
- Detector Maintenance and Operation: **5M** USD.

The resources needed for **2023-2030** for operation phase are estimated as **6.4M USD** in total. The breakdown:

- Travel expenses **1.4M** USD.
- Experiment fee **5M** USD.

NOvA/DUNE/HyperKamiokande

Motivation

The **NOvA** experiment is an accelerator-based neutrino experiment with off-axis beam sent from Fermilab to Minnesota across about 810 km. The primary goal of NOvA is neutrino mass ordering determination and measurement of CP-violation in the lepton sector.

The next breakthrough in the determination of the neutrino mass ordering and CP-violation in the lepton sector can be expected from a global analysis of neutrino data and from precision measurements at accelerator long-baseline experiments like **DUNE** in the United States or **HyperKamiokande** in Japan.

JINR, successfully participating in the **NOvA** experiment, is considering to join at least one of these. The decision is expected to be taken based on a possible sizeable JINR contribution to the hardware and analysis, needed for being respected as a leading laboratory.

International Context

Both **DUNE** and **HyperKamiokande** are truly international collaborations. All JINR member-states will have a possibility to become collaborators of **DUNE** or **HyperKamiokande** if join the corresponding JINR group.

Proposed Research

NOvA is expected to stop data taking around 2024-2025.

JINR plans the following research in the **NOvA** experiment during the mid-term period:

- Continue data analyses on neutrino mass ordering, CP-violating phase for the lepton sector.
- Continue searches for SN.

In parallel to data analyses in the **NOvA** experiment, JINR plans to perform R&D for future experiments with neutrino from accelerators **DUNE** or **HyperKamiokande.** JINR is expected to contribute substantially to the detector construction and physics analysis. The exact detector module is yet to be identified during the mid-term period, close to the termination of the **NOvA** experiment.

The following possibilities are being considered:

- **DUNE** experiment:
  - Straw-tube tracker system for the Near Detector.
  - Light detection system of the Near Detector ArgonCube TPC.
- **HyperKamiokande** experiment:
  - R&D of the read-out system.
  - PMT testing facility.
  - Purchase of a portion of PMTs.

For the physics research, based on the present successful experience in NOvA, the JINR team can continue with:

- Development of reconstruction and particle identification algorithms.
- Measurement of neutrino mass ordering and CP-violation in the lepton sector
- Search for exotic phenomena: Supernova triggering and analysis, etc.

Required Resources

JINR is expected to contribute substantially in the detector R&D and construction at the level of

- **10M** USD during the long-term period.
- **1.5M** USD during the long-term period.

Edelweiss, GERDA, SuperNEMO, DANSS, nuGEN, RICOCHET, GEMMA-III, KATRIN

Motivation

GERDA and **SuperNEMO** search for neutrino nature- either it is a Dirac or Majorana particle, in attempts to detect neutrino-less double beta decay of carefully selected best candidate nuclei.

KATRIN experiment attempts to provide the best determination of neutrino mass from a careful measurement of electron's energy spectrum from tritium decays.

Experiments at Kalinin Nuclear Power Station investigate the magnetic moment of neutrino (**GEMMA-III**), coherent antineutrino-nucleus scattering (**nuGEN**) and search for a hypothetical sterile neutrino state (**DANSS**). **RICOCHET** experiment will supersede the nuGEN experiment aiming at more precise measurements of CEvNS, and searches for New Physics with CEvNS, via bolometric technique and nuclear recoils from 20 eV.

Proposed Research

- Data analyses, calibration, software for simulation and reconstruction (for all).
- Design and production of high-purity germanium bolometers (Edelweiss, GERDA), detector constructions (GEMMA-III, nuGEN, DANSS, GERDA, SuperNEMO).

Required Resources

- For the mid-term period JINR expects to invest **10.5M** USD into R&D, detectors commissioning and construction.
- For the long-term period JINR investments are estimated as **7M** USD.

DarkSide-20k, ARGO

Motivation

DarkSide-20k experiment searches for dark matter signals exploiting 20 tons liquid argon time projection chamber and germanium bolometers, respectively. Its data taking is expected till 2028. During the mid-term, R&D for new much larger and more sensitive detector **ARGO** is expected. Its commissioning is expected by mid-2029.

Proposed Research

- For the mid-term period, data analyses of DarkSide-20k.
- For the long-term period, R&D of ARGO detector components. The components are yet to be determined. Data analyses of ARGO detector.

Required Resources

- R&D, detector construction and commissioning are estimated to be **0.7M** USD for the mid-term period.
- Data taking is estimated to be **0.7M** USD for the long-term period.

TAIGA

Motivation

TAIGA experiment searches for sources of gammas within the energy interval in (1-100) TeV. Such sources are hypothesized to be related to those of UHE neutrinos, thus making an important contribution to multi-messenger astronomy.

Proposed Research

- Data analyses, calibration, software for simulation and reconstruction.
- Design and production of 14 gamma imaging telescopes.
- Search for source of gammas within the energy interval in (1-100) TeV.

Required Resources

JINR is expected to contribute in the detector R&D and construction of IACT telescopes at the level of

- **1.8M** USD during the mid-term period.
- **1.8M** USD during the long-term period.

Gravitational Wave Detector

Motivation

General theory of relativity predicts the existence of gravitational waves (disturbances of space-time) propagating with the speed of light. Gravitational waves (GW) are produced by violent processes occurring in the Universe, like coalescence of black-holes, neutron stars, supernova explosions, releasing extreme energies like several masses of the Sun in the form of GW.

Observations of GWs by LIGO and Virgo (see Refs.[10], [11], [12] and referenced therein) explained the origin of short gamma-ray-bursts, proved the mechanism of heavy elements synthesis via the so called r-process nucleosynthesis, has revealed a previously unknown population of stellar-mass BHs, and provided the first measurement of the Hubble constant with GWs. A new observation channel in the multi-messenger astronomy is definitely come to life.

However, all these great discoveries are just the first steps of the newly born gravitational astronomy. Next generations of GW detectors are planned, like Einstein experiment [13], schematically displayed in Fig.3, which is expected to be orders of magnitude more sensitive than the current second generation of GW detectors.

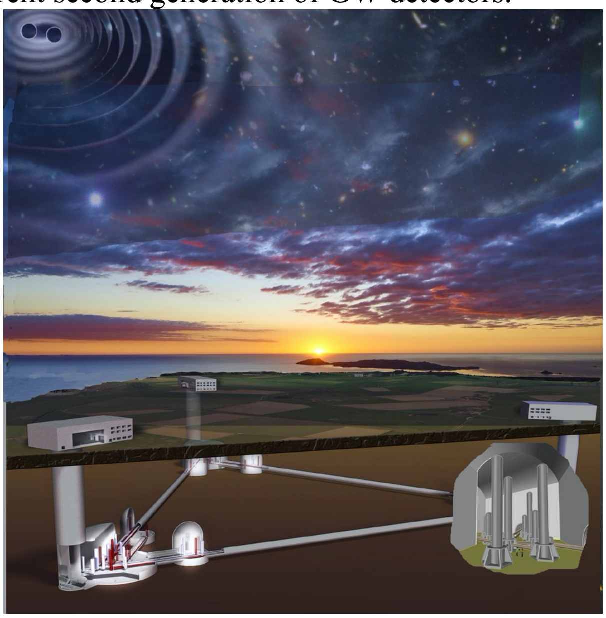

Fig.3 Schematic view of Einstein telescope.
Image credit: Einstein Telescope project.

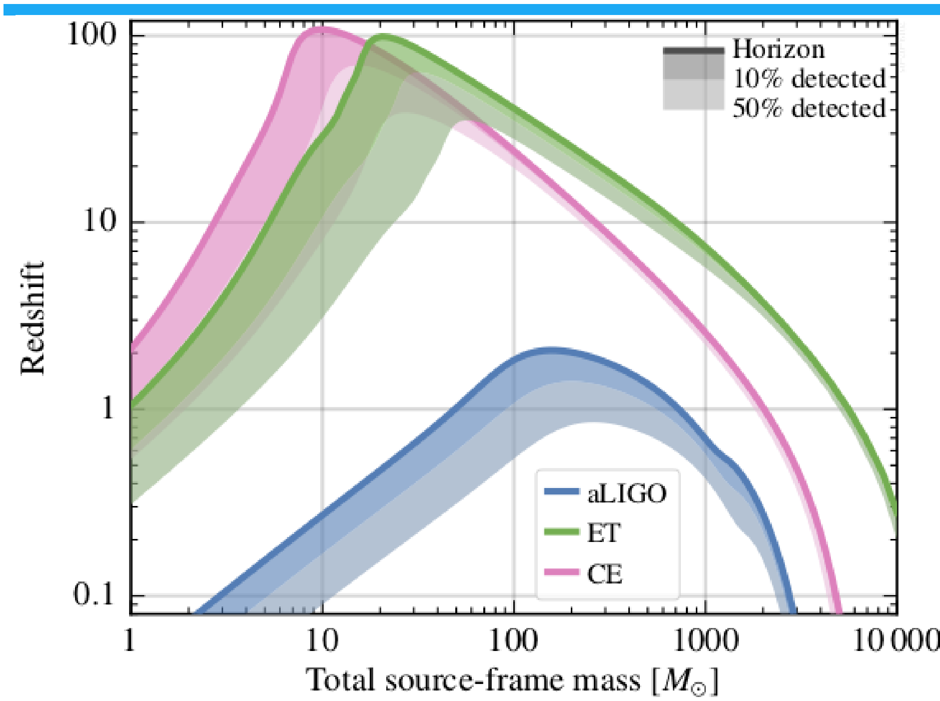

Fig.4 Astrophysical reach for equal-mass, non-spinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer. Figure from Ref. [13,14].

Fig.4 displays the astrophysical reach for equal-mass, non-spinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer.

JINR should not remain outside of this great new science. JINR is in the process of joining VIRGO through the precision laser inclinometry devices invented at DLNP JINR. During the mid-term period JINR will increasingly gain competence in this new field.

During the long-term period, JINR should be fully integrated into this activity, increasing its competence by appropriate participation in already existing GW detectors, joining Einstein GW detector design and construction, and hopefully developing own, Russia-based GW detector.

International Context

This activity should be placed into a fully international environment, involving scientists from JINR member-states.

Proposed Research

- R&D of various detector components: vacuuming, ultra-cold temperature detectors, laser interferometry, precision mechanics, stabilization, photon detection devices.
- Gain the competence in GW physics and related detection technologies.
- Development of CDR of GW detector.
- Data analysis of VIRGO and Einstein.

Required Resources

- **1.4M** USD are expected to be invested for R&D during the mid-term period.
- **35M** USD are expected to be invested for R&D and detector construction during the long-term period.

Summary

The proposed long-term Strategy for Neutrino Physics and Astrophysics at JINR is based on a world recognized JINR Neutrino School established by Bruno Pontecorvo. It is enhanced further by world class experimental program in Neutrino Physics, Multi-Messenger Astronomy, including Gravitational Wave Detection and Detector Technologies, supplemented by a well though educational and outreach program.
This strategy carefully strengthens traditional JINR strong expertise in neutrino physics. At the same time, it pushes further the frontiers by developing new expertise in newly born fields like multi-messenger astronomy and gravitational wave detections where great and deep insights on the Universe formation and evolution is expected. The strong interplay with particle physicists in the same laboratory is of great intellectual benefit.

Timeline
Tables 1 and 2 provide compact summaries on the timelines of the mid- and long-term experimental activities. The cell colors in tables 1,2 are explained here:

Cell color	R&D	Construction Commissioning	Data taking	STOP	Decision Point

	24	25	26	27	28	29	30	Main physics goal **Budget, USD**
BAIKAL-GVD								UHE Neutrino sources **45M**
	Phase II				Phase III			
	R&D for Phase III							
JUNO								Neutrino mass ordering, precision lepton mixing, SN, proton decay **7.5M**
NOvA			Stop data taking. Data analysis continue					
DUNE								Neutrino mass ordering, CP-violation in the lepton sector **10M**
HyperKamikaonde								

DarkSide-20k **ARGO**	DarkSide-20k data taking ARGO R&D	Dark matter search **0.7M** USD
TAIGA	Data taking TAIGA IACT+ TAIGA HiSCORE One TAIGA IACT gamma-telescope/year	High energy cosmic ray and gamma spectrum above 10^{15} eV **1.8M**
Edelweiss	R&D for new detector and cryogenic system / Next phase of bolometric search in LSM	Dark matter search
GERDA	R&D Legend-1000 / LEGEND-1000	Search for neutrinoless double-beta decay
SuperNEMO		
DANSS	Data taking with DANSS-2 and NEUTRINO-6 Construction, tests	Search for sterile neutrinos, monitoring of nuclear reactors.
nuGEN **RICOCHET**	 Phase I @ILL / Phase II @ Nuclear Power Plant	Coherent neutrino-nucleus
GEMMA-III	Runs with new generation of detectors, with continuous increasing of detectors' mass and sensitivity.	Magnetic moment of neutrino
KATRIN	Data taking in 3 months cycles, calibrations, methodical studies, systematic understanding and compacting of data.	Direct measurement of neutrino mass. Search for heavy neutrinos. **10.5M**
VIRGO		Observation of GW, cosmological studies **1.4M**

Table 1. Timeline of projects from the mid-term Strategy for elementary particle physics and astrophysics at JINR.

	31	32	33	34	35	36	37	Main physics goal **Budget, USD**
BAIKAL-GVD								UHE Neutrino sources **45M**
	Phase II				Phase III			
	R&D for Phase III							
JUNO								Neutrino mass ordering, precision lepton mixing, SN, proton decay **6.4M**
DUNE/Hyper Kamiokande								Neutrino mass ordering, CP-violation in the lepton sector **1.5M**
ARGO								Dark matter search **0.7M**
Edelweiss			Based on situation with DM					Dark matter search
TAIGA								High energy cosmic ray and gamma spectrum above 10^{15} eV **1.8M**
	One TAIGA IACT gamma-telescope/year							
LEGEND-1000								Search for neutrinoless double-beta decay **3M**
SuperNEMO								
KATRIN								Direct measurement of neutrino mass. Search for heavy neutrinos. **4M**
VIRGO EINSTEIN								Observation of GW, cosmological studies **35M**

Table 2. Timeline of projects from the long-term Strategy for elementary particle physics and astrophysics at JINR.

International Context

The presented JINR Strategy for Neutrino-Physics and Astro-Physics is a careful balance of home and foreign experiments. All JINR member-states have a unique possibility to enjoy both a rich, modern JINR infrastructure and participation in the world-class leading experiments in the fields of neutrino physics and astrophysics.

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