Annex 3.

Form of renewal for Project

APPROVED
JINR DIRECTOR
/
"_____"_____ 2026

SCIENTIFIC AND TECHNICAL REASONING FOR THE RENEWAL OF THE PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the project
1.1. Theme code 02-2-1099-2010.

1.2. Project code 02-2-1099-1-2010/2031.
1.3. Laboratory DLNP

1.4. Scientific field particle physics

1.5. The name of the Project Study of neutrino oscillations in the JUNO experiment (participation of JINR)

1.6. Project Leader(s) D.V. Naumov

1.7. Project Deputy Leader(s) N.V. Anfimov, M.O. Gonchar

1.8. Scientific supervisor of the project D.V. Naumov

2. Scientific rationale and organisational structure

2.1. Annotation

JUNO, a reactor antineutrino experiment in China, aims to determine the neutrino mass ordering with median sensitivity corresponding to 3−4 standard deviations alone and measure lepton mixing parameters with record sub-percent precision level. There is also a rich physics program including searches for proton decay, search for SN neutrino, most precise measurement of geo-, atmospheric and solar neutrino fluxes, as well as searches for physics beyond the Standard Model.

The satellite detector TAO will measure reactor electron antineutrino spectrum with unprecedented statistical uncertainty of order of 1% and energy resolution of σ=2% at energy of 1 MeV. It will also be sensitive to sterile (anti)neutrinos in the range of squared mass difference values Δm^2_{41} of the order of a few eV².

Currently, the experiment is in the physics data-taking phase. The JUNO detector has been taking data since August 2025, and the TAO near detector since March 2026. Both detectors have

reached their design performance specifications. After only two months of data taking, JUNO measured two neutrino oscillation parameters, $\sin^2\theta_{12}$ and Δm^2_{21} with world-leading precision. Consequently, the primary future goal of the project is to execute the planned physics program.

JINR plays a major role in this project:

(i) JINR is responsible for design and production of high voltage units for JUNO large (20 inches) and small (3 inches) photomultipliers (PMTs) with an overall amount exceeding 25 thousand units;

(ii) JINR contributes to the construction of the Top Tracker (TT) detector by developing a mechanical support system, hardware and software for monitoring of T scintillators, tracks reconstruction and data acquisition system (DAQ);

(iii) Mass tests and commissioning of large PMTs with help of JINR's designed and produced brand new scanning stations;

(iv) JINR contributed to the design and construction of JUNO's near detector — TAO: procurement of half of 4100 tiles (130k dices) of silicon photomultipliers (SiPM) and their mass-testing, production and operation of SiPM power supply system (4100 channels);

(v) JINR commissioned a dedicated data center for the simulation, storage, and processing of JUNO experiment data. The JINR facility operates as one of the three European data centers supporting JUNO's computing needs.

(vi) JINR actively contributes to software development. This includes the creation of the Global Neutrino Analysis (GNA) and dag-modelling frameworks for statistical oscillation analysis, the development of event reconstruction and data analysis algorithms, and the implementation of a Data Quality Monitoring (DQM) service;

(vii) JINR directly participates in the processing and analysis of the data, from data quality and to event selection and statistical analysis.

JINR contributed to the JUNO project about 10M$. These investments not only enabled us to provide necessary parts of the JUNO detector, but also helped to significantly develop the infrastructure of the Laboratory and the Institute for methodological works with photomultiplier tubes, SiPM, electronics, computing resources and much more. The detector is currently in the data-taking phase. Future expenditures will primarily pertain to detector maintenance and operations, as well as travel expenses for data-taking shifts, collaboration meetings, and scientific conferences.

In the following five years the project will be focused on realization of the mai physics programme of the JUNO and TAO experiments, including precision measurement of oscillation parameters and reactor antineutrino spectrum, refinement of the energy response of the detector by considering the intrinsic energy resolution of liquid scintillator, development of calibration methods, monitoring and validation of the data quality, improvement of the muon reconstruction and veto system, development of the computing and software infrastructures for the analysis. Significant amount of work will be devoted to the joint analysis of data of JUNO, TAO and Daya Bay, studies of atmospheric neutrinos, improving sensitivity to neutrino mass ordering and search for the physics beyond Standard Model, including sterile neutrinos, non-standard interaction and possible neutrino decay.

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

Goals

JUNO aims to determine the neutrino mass ordering with median sensitivity corresponding to 3−4 standard deviations alone and measure lepton mixing parameters with record sub-percent precision level. There is also a rich physics program including searches for proton decay, search for SN neutrino, precise measurements of geo-neutrino, atmospheric and solar neutrino fluxes, as well as searches for physics beyond the Standard Model.

Relevance and scientific novelty

Neutrino mass ordering

The term "neutrino mass ordering" (MO) refers to establishing an appropriate ordering of masses of neutrino mass states $m_3 > m_1$ or $m_1 > m_3$. There is no easy and cheap way to measure the ordering. The MO can be determined using the following observables.

(i) **Neutrino oscillation** probability is sensitive to the MO in both appearance and disappearance channels. The disappearance channel is insensitive to the CP-violation phase which is currently unknown. On the contrary, the appearance channel suffers from the degeneracy due to an unknown CP-violating phase which biases the MO for neutrino energy of GeV range and the baseline of 700 km. At a larger baseline the degeneracy is relaxed due to an increasing matter effect.

JUNO[1] exploits the disappearance channel using reactor electron antineutrinos. After six years of data taking JUNO should be able to determine the mass ordering at 3 standard deviations without external constraints on the value of Δm^2_{31}.

NOvA[2] and T2K[3] accelerator neutrino experiments are taking data and currently both favouring the normal mass ordering ($m_3 > m_1$) at about 1.4 and 1.6 standard deviations respectively. As a result of a joint Bayesian analysis of NOvA and T2K data, the inverted ordering is preferred, providing better agreement between the measured oscillation parameters. This preference, however, is not statistically significant.

The DUNE[4], an accelerator neutrino experiment, should start data taking in 2030. DUNE will be able to determine the MO at 5 standard deviations in about two years after the start of the data taking.

Two atmospheric neutrino experiments are sensitive to mass ordering. IceCube is projected to achieve a sensitivity of 1.5 to 3.5 standard deviations within six years of data collection, by 2031. ORCA, a part of the KM3NeT detector with a denser PMT array, could reach a sensitivity of 3 to 5.5 standard deviations in 2032, provided that data collection begins in 2027.

The JUNO detector will also be sensitive to atmospheric neutrino oscillations, which could provide additional sensitivity to the mass ordering when combined with reactor antineutrino data. Nevertheless, its actual contribution to the MO determination sensitivity requires detailed evaluation.

The HyperK project, the successor to the SuperK and T2K experiments, can also utilize both accelerator and atmospheric neutrinos to determine the MO. HyperK's sensitivity to the MO is estimated to be between 3 and 4.5 standard deviations after six years of data collection, which is expected to begin in 2027.

A comparison of the experimental sensitivities as a function of date is presented in Figure 1.

[1] https://iopscience.iop.org/article/10.1088/0954-3899/43/3/030401
[2] https://novaexperiment.fnal.gov
[3] https://t2k-experiment.org
[4] https://www.dunescience.org

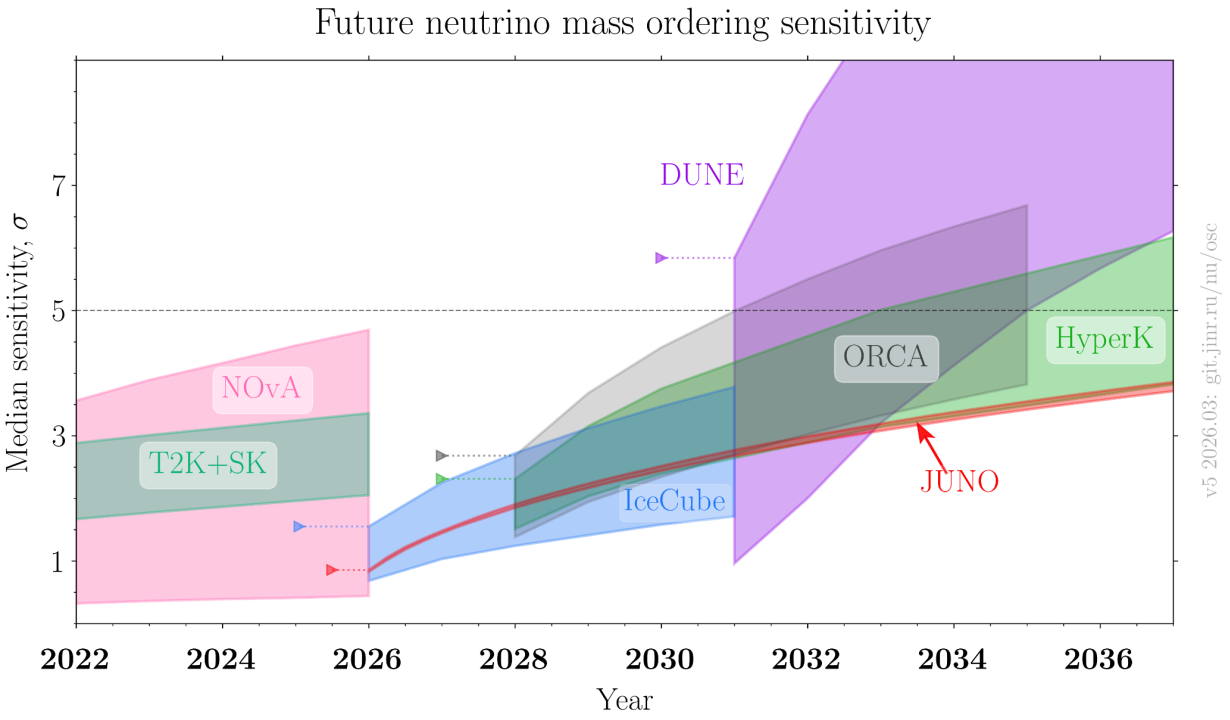


Figure 1. Sensitivity of future reactor, accelerator, and atmospheric neutrino oscillation experiments to the neutrino mass ordering. While the sensitivity projections for other experiments may be preliminary, the figure still provides a clear idea of the overall picture.

(ii) **Neutrinoless double beta decay** probability is sensitive to the MO. If observed the effective neutrino mass $m_{\beta\beta}$ is expected to be of the order $2.6 \cdot 10^{-2}$ eV for the inverted mass ordering, and $2.6 \cdot 10^{-3}$ eV for the normal mass ordering. Current experiments do not provide competitive limits on the MO.

(iii) **Cosmology** provides limits on the sum of neutrino masses Σm_ν. One expects that $\Sigma m_\nu \geq 0.06$ eV for the inverted MO and $\Sigma m_\nu \geq 0.1$ eV for the normal MO. Current bounds on Σm_ν does not provide yet a competitive limit, while a further increase in the Σ_ν determination accuracy is proved to be significant. The key players here are CMB-S4[5] and CORE[6] experiments. Their start data taking dates are not known to us.

(iv) **Beta decay experiments** are also sensitive to the MO since each neutrino mass eigenstate produces a kink in the energy spectrum. The corresponding measurement is extremely challenging since a record energy resolution is required to resolve these kinks. The KATRIN experiment will not provide a competitive limit, while the Project-8[7] experiment, which will use the Cyclotron Radiation Emission Spectroscopy in order to determine the mass of the electron antineutrino, might be able to provide the competitive limit. We refrain from discussing the time scale.

Let us note, that while sensitivities of individual experiments might be below the 5σ discovery significance, the joint analysis of their data is known to improve the overall sensitivity to the MO at a rate more significant than the usual statistical averaging of the data. The main reason for that is a significant breaking of the degeneracy in parameters determination when data from different categories (i)-(iv) are combined.

This consideration was one of our motivations to develop the JINR global analysis framework

[5] https://arxiv.org/pdf/1610.02743.pdf
[6] https://arxiv.org/abs/1706.04516
[7] https://arxiv.org/abs/1309.7093

(GNA). Today, the global neutrino fits favour the normal ordering at 2.4σ[8]. Further details can be found in Ref.[9]

Accuracy of the lepton mixing parameters determination

The current measurement precision of the lepton mixing parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ is presented in Figures 2–4. The figures also include JUNO's first measurement of Δm^2_{21} and $\sin^2 2\theta_{12}$, alongside its expected sensitivity after six years of data taking, which will improve the measurements to the sub-percent level and establish world-leading precision. Furthermore, JUNO is sensitive to the value of $\sin^2 2\theta_{13}$ with a precision of 11.7%. Currently, the Daya Bay experiment provides the leading measurement of $\sin^2 2\theta_{13}$ with a precision of 2.8%. As can be seen from the figures, JUNO will achieve a dominant precision that is expected to remain unsurpassed for decades.

It is worth noting that JUNO's high sub-percent precision in measuring oscillation parameters, particularly the mass-squared difference Δm^2_{31} at the 0.2% level, provides essential input for long-baseline oscillation experiments, including both accelerator and atmospheric setups. This highly accurate data will enable a significant improvement in the precision of the MO determination[10].

Consequently, the precise measurement of neutrino oscillation parameters in JUNO is of equal importance to the determination of the MO itself.

[8] https://globalfit.astroparticles.es/2018/07/03/neutrino-mass-ordering/
[9] http://www.nu-fit.org/?q=node/309
[10] https://arxiv.org/abs/2404.08733

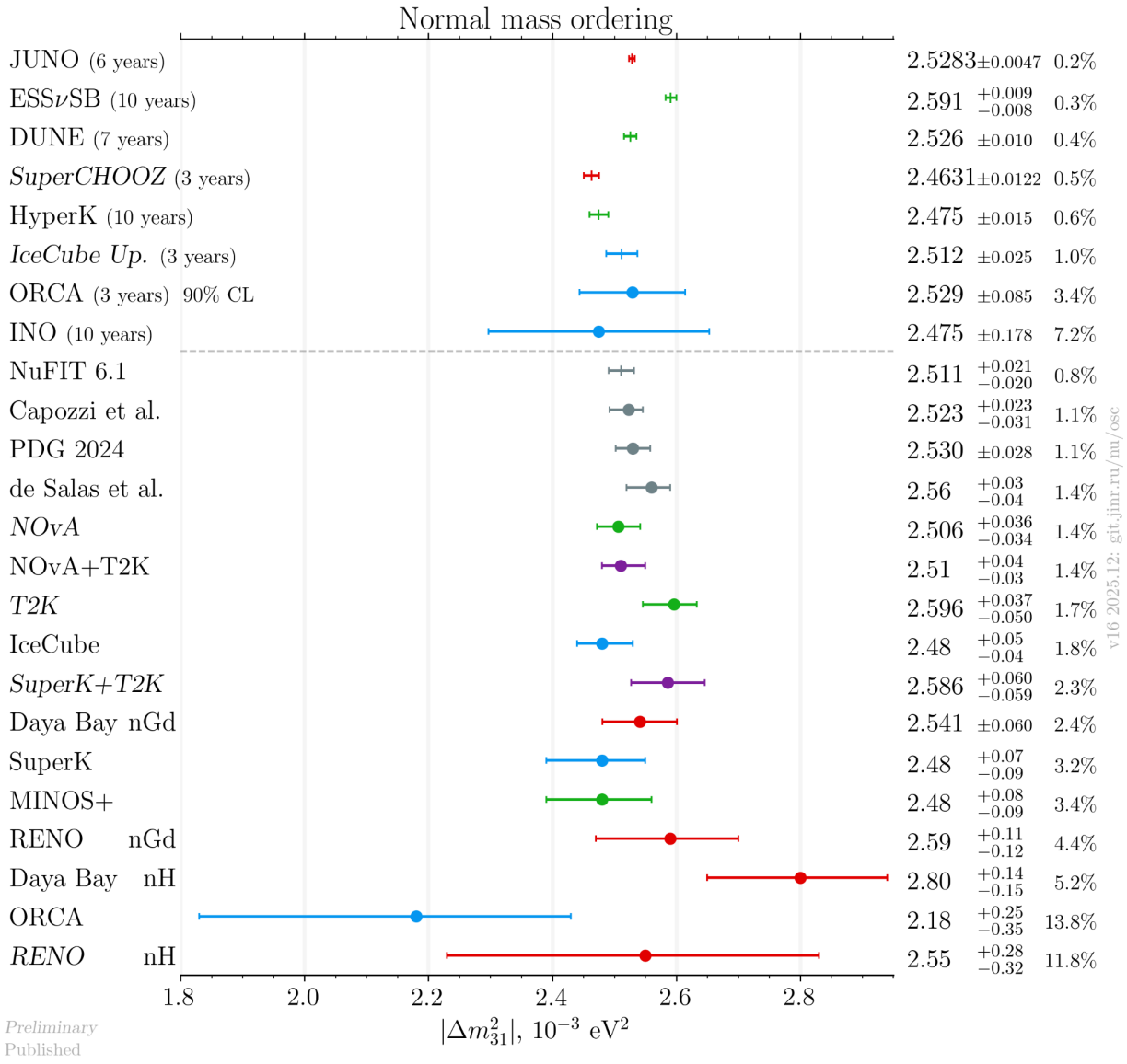


Figure 2. Accuracy of the measurement of the neutrino oscillation parameter Δm^2_{31} under assumption of normal MO.

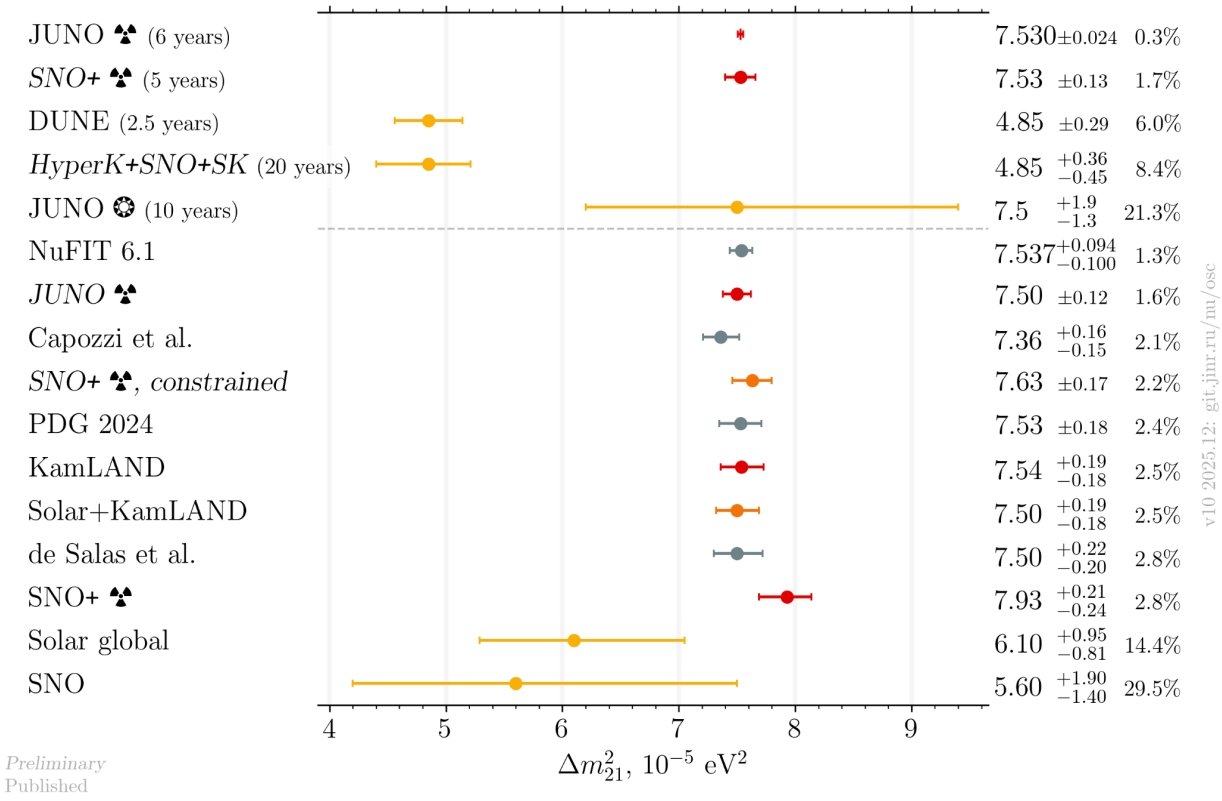


Figure 3. Accuracy of the measurement of the neutrino oscillation parameter Δm^2_{21}.

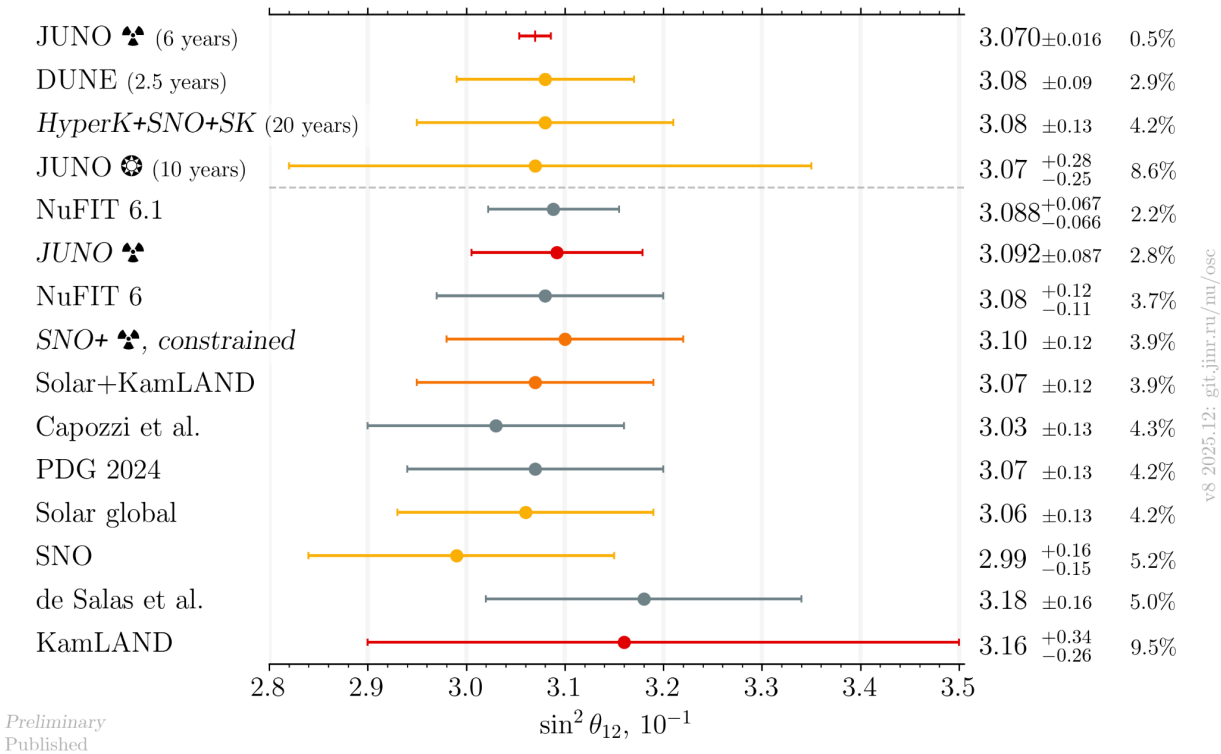


Figure 4. Accuracy of the measurement of the neutrino oscillation parameter $\sin^2\theta_{12}$.

Proton decay

To explain the observed matter-antimatter asymmetry of the universe, baryon number violation is one of the requirements. There is no experimental evidence for baryon number violation yet.

The decay mode $p \rightarrow K^+\nu$ is favoured by a number of SUSY GUT's which typically predict the lifetime of the proton to be less than a few of 10^{34} yrs. The search for this mode in a large water Cherenkov detector is hindered by the decay kinematics. The momentum of the K^+ in this two-body decay is 339 MeV/c (kinetic energy of 105 MeV), which is below the Cherenkov threshold in water. Today's best limit is $\tau(p \rightarrow K^+\nu) > 5.9\times10^{33}$ yrs at 90% C.L. reported by the Super-Kamiokande collaboration[11].

A liquid scintillator detector is able to observe this channel using a unique triple time coincidence signature of the decay. In general, the LS detector efficiency is significantly higher than that of the Cherenkov detector. Due to the high efficiency in measuring this mode, JUNO's sensitivity will surpass Super-Kamiokande in only 3 years since its data taking. In 10 years JUNO will reach the sensitivity of $8.34\cdot10^{33}$ years at 90% C.L.

SN neutrino

So far, neutrinos from a single SN1987A explosion were detected in 1987 by Kamiokande II (12 events), IMB (8 events) and Baksan (5 events). 25 detected neutrinos in total.

SN observations with neutrinos potentially is a rich source of information about the collapsing mechanisms of stars, strong matter effects for neutrino oscillation, and independent determination of the MO. A new generation of large scale detectors able to detect hundreds or thousands of SN neutrinos will determine our understanding of SN processes.

JUNO 20 kt detector will be able to detect about 10 thousand SN neutrinos in different channels in 10 s time window, assuming SN at 10 kpc. For the SN bursts within 1 kpc JUNO will be sensitive to the neutrinos emitted before the collapse of the star.

Also, JUNO will have 5σ sensitivity to diffuse supernova background (DSNB) in ten years of data taking. During the period of 3 years JUNO will reach a sensitivity of 3σ.

Geo-, atmospheric and solar neutrinos

Geo-neutrino, electron antineutrino produced in decays of long-lived radionuclides in the Earth interior, was discovered by KamLAND[12] and BOREXINO[13] experiments. Latest analyses reveal 169 and 53 events attributed to geoneutrinos in KamLAND and BOREXINO data, respectively.

The new emerging field of science, **neutrino geophysics**, requires much larger statistics, see a review[14] for more details. JUNO will collect about 400 geoneutrinos per year (40 TNU/year). Over six years of data collection, JUNO will be able to measure the geoneutrino flux with a precision of 11% (14%) in the presence (absence) of an external constraint on the Th/U ratio, accumulating the largest sample of geoneutrino interactions[15].

JUNO will be the first liquid scintillator experiment sensitive to atmospheric neutrinos. The detection of atmospheric neutrinos will enhance JUNO's sensitivity to determining the MO and the θ_{23} octant. The PINGU and ORCA experiments, which are directly targeted at measuring atmospheric neutrinos, will play a leading role in this field of research. Through its observation of atmospheric

---

[11] E. Kearns, talk presented at the ISOUP Symposium (2013).

[12] H. Watanabe, talk at Neutrino Geoscience 2019, Prague, "Geoneutrino measurement with KamLAND", https://indico.cern.ch/event/825708/contributions/3552210/attachments/1930535/3197332/HirokoWatanabe_NGS2019.pdf

[13] M. Agostini et al., Borexino collaboration, "Comprehensive geoneutrino analysis with Borexino", Phys. Rev. D 101, 012009 (2020) DOI: 10.1103/PhysRevD.101.012009

[14] O.Smirnov, "Experimental aspects of geoneutrino detection: Status and perspectives", Progress in Particle and Nuclear Physics 109 (2019) 103712. https://doi.org/10.1016/j.ppnp.2019.103712

[15] http://arxiv.org/abs/2511.07227

neutrinos, JUNO will make a modest contribution to the MO determination at approximately the 1σ level. However, when combined with reactor antineutrino measurements, the resulting increase in sensitivity is expected to be greater than a simple sum, due to the complementary underlying physics.

It is now well established that the deficit in the solar neutrino flux is attributed to neutrino oscillations within solar matter. However, outstanding questions remain, including: (i) the solar metallicity problem, and (ii) the lack of data in the neutrino energy region corresponding to the transition from vacuum oscillations to the matter oscillation regime.

JUNO will be able to collect 1000 events per day from ^{7}Be and 10 events from ^{8}B solar reactions. These observations will shed new light on both the solar metallicity puzzle and the transition regime of neutrino oscillations.

Reactor antineutrino spectrum

Energy spectrum of reactor electron antineutrinos measured in modern experiments is known to have a deviation from the predictions of the widely used Huber+Mueller model[16]. The feature is located at 4−6 MeV of neutrino energy referred to as a "bump" and currently has no proper explanation. Thus the precision measurement of the reactor electron antineutrino spectrum is needed as an input to the reactor experiments and for understanding of the reasons behind this deviation. The satellite detector TAO will have an unprecedented energy resolution of σ=2% at 1 MeV and will provide the best measurement with statistical uncertainty of 1%.

Beyond Standard Model

A wide array of studies are dedicated to the search for physics beyond the Standard Model (BSM), including the existence of a fourth (sterile) neutrino state, non-standard interactions (NSI), and neutrino decay, among others. The TAO satellite detector, featuring unprecedented performance and accumulating extensive statistics of reactor electron antineutrino interactions, will enable the placement of new, tighter constraints on the corresponding parameters.

Methods and approaches

The JUNO experiment

Main objectives of JUNO experiment are (i) determination of neutrino mass ordering; (ii) determination of Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ with sub-percent precision; (iii) search for proton decay; (iv) search for SN neutrino; (v) detection of geo-, atmospheric and solar neutrinos; (vi) searches for physics beyond the Standard Model.

The JUNO central detector (CD), shown in Figure 5, is a spherical acrylic tank with 35m diameter filled with 20 thousand tons of liquid scintillator (LS). The scintillation light is detected by about 18k 20'' PMTs (LPMT) and about 26k 3'' PMTs (sPMT) providing about 78% surface coverage. The CD is placed at 52.5 km from Yangjian and Taishan NPP reactors with a total power of 26.6 GW.

[16] https://arxiv.org/abs/1106.0687, https://arxiv.org/abs/1101.2663

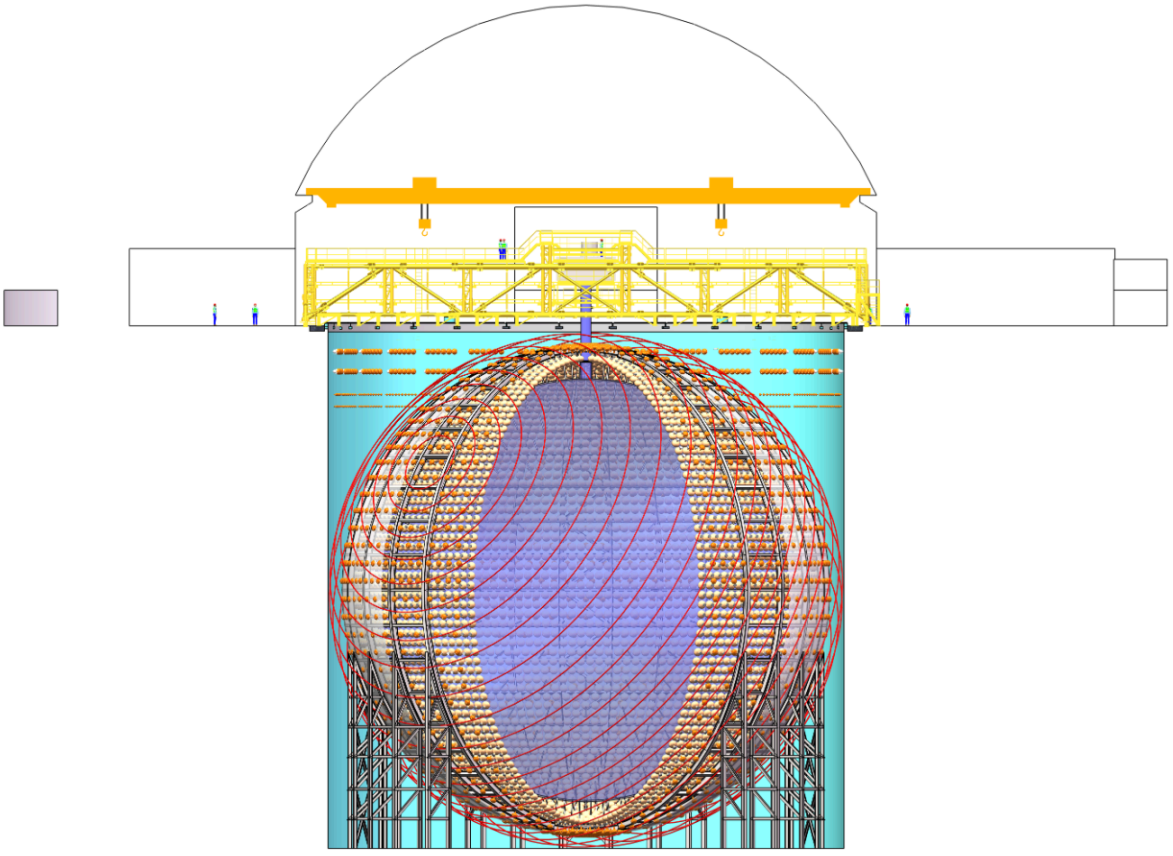


Figure 5**.** The JUNO central detector and the Top Tracker. The acrylic vessel has a diameter of approximately 35 meters. The detector is surrounded by a system of Helmholtz coils designed to compensate for the Earth's magnetic field (EMF).

In seven years of the data taking JUNO will collect about 100k of inverse beta decay (IBD) events determining the antineutrino energy with precision better than σ=3%[17] at 1 MeV of the energy visible in the LS. The precise measurement of the IBD energy spectrum allows the determination of the neutrino mass ordering as can be seen in Figures 6 and 7. It should be noted that it is not sufficient to simply distinguish a single histogram for the normal MO from one for the inverted MO; rather, a comprehensive statistical analysis must be performed, accounting for all sources of systematic uncertainty under each MO hypothesis.

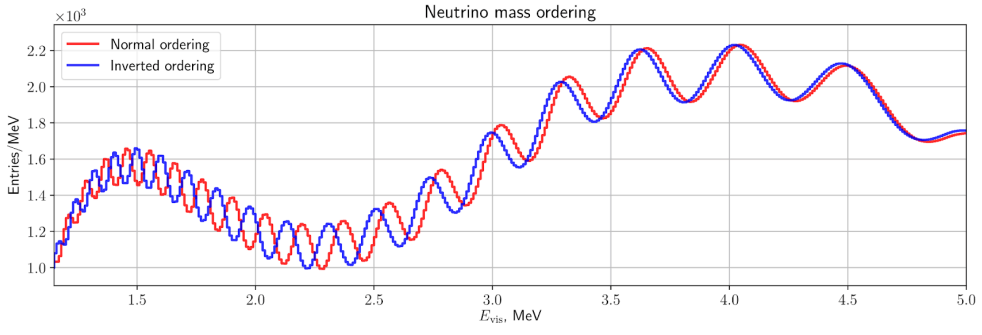


Figure 6. Expected energy spectrum in JUNO after eight years of data collection for the two neutrino mass ordering scenarios. The true energy is shown, neglecting detector effects.

[17] This is a design estimate. For further details, please refer to the section titled "Intrinsic Scintillator Resolution and Detector Response.

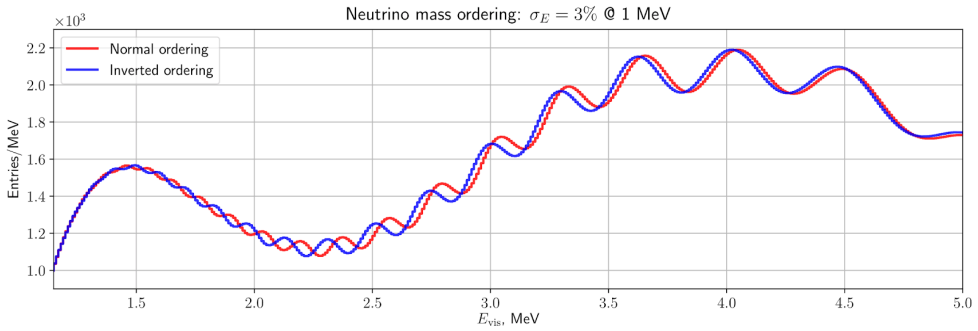


Figure 7. Expected energy spectrum in JUNO after eight years of data collection for the two neutrino mass ordering scenarios. The plot corresponds to the reconstructed energy with a resolution of σ=3% at 1 MeV.

JUNO's sensitivity is free from degeneracies associated with the unknown values of the CP-violating phase and $\sin^2\theta_{23}$. The primary limitation of this method is the energy resolution, which must be achieved at the 3% level at 1 MeV of visible energy.

Another challenge is the possible existence of a "fine structure" within the reactor antineutrino energy spectrum. If present, this structure could potentially distort the mass ordering determination and/or degrade the experiment's sensitivity. To eliminate the reliance on antineutrino spectrum models and mitigate the impact of any potential fine structure, the TAO satellite detector has been developed; it will measure the reactor antineutrino energy spectrum with a precision at least as good as that of JUNO.

Near detector TAO

The TAO detector is a spherical barrel of 1.8 meters (see in Figure 8) filled with the 2.8 tonnes of gadolinium-doped LAB liquid scintillator similar to the CD in order to have similar systematic uncertainties. To reach a resolution better than in the central detector, TAO will exploit silicon photomultipliers (SiPM) with photon detection efficiency PDE (about 50%) higher when compared to conventional vacuum phototubes (PMTs). One of the primary challenges of this approach is the exceptionally high Dark Count Rate (DCR) at room temperature, which can degrade the energy resolution and negate all the advantages of a high PDE. To suppress the DCR by three orders of magnitude, the detector operates at a low temperature of −50°C.

The detector surface area covered by SiPMs is approximately 11 m². In total, about 130000 SiPM chips measuring 12×6 mm² are utilized, packaged into 4100 arrays (referred to as tiles) of 5×5 cm², with 32 elements each. This vast number of SiPMs is read out using 4100 32-channel ASICs or 4100 discrete ADC channels, each reading out a tile as a single unit. JINR provided the power supplies for all the tiles, featuring adjustable voltage up to 120 V. All SiPM tiles were studied in detail, with JINR playing a key role in the preparation of the mass testing procedures.

To ensure that the entire energy of the gamma rays from positron annihilation in the inverse beta decay reaction is fully converted into scintillation light, the fiducial volume is reduced by 25 cm in radius relative to the full detector dimensions, containing 1 ton of liquid scintillator (LS). The IBD event rate within this fiducial volume is expected to be 1000 (2000) events per day with (without) detection efficiency included, allowing for the accumulation of over 2 million events over seven years of data collection. Consequently, TAO will provide a measurement of the reactor electron antineutrino spectrum with a statistical uncertainty of approximately 1% and an energy resolution of σ=2%[18] at 1 MeV of deposited energy.

[18] This is a design estimate. For further details, please refer to the section titled "Intrinsic Scintillator Resolution and Detector Response.

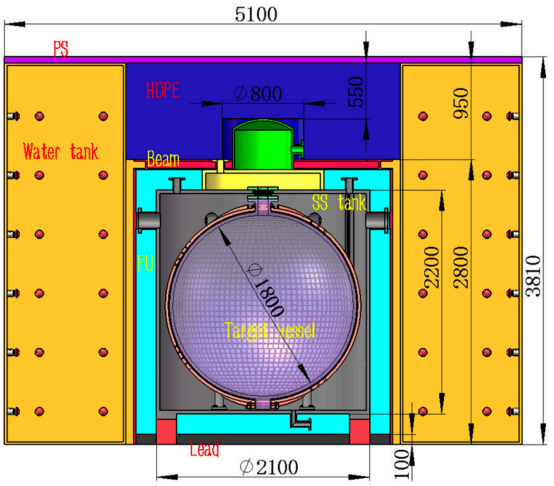


Figure 8. Schematic view of the TAO detector.

Reactor electron antineutrinos on the short baseline (TAO detector)

Antineutrinos in the TAO detector are detected using the inverse beta decay reaction (IBD). A signal of interest is found by detecting delayed coincidences of two pulses in the target (scintillations). The first, or prompt, occurs from positron annihilation. The energy of this event is proportional to the neutrino energy. The second or delayed pulse appears from a series of gammas with a total energy of about 8 MeV, emitted after neutron capture on gadolinium. The lifetime of a neutron before capture is 22 μs. Such a reaction signature makes it possible to significantly reduce background levels. After the selection of IBD events, the residual backgrounds are represented by accidental coincidences, long-lived cosmogenic isotopes ^{9}Li/^{8}He (β-n decay), fast neutrons and antineutrinos from spent nuclear fuel (SNF) in the spent fuel pool. Antineutrinos from the second (far) power unit of the NPP also make a small contribution to the signal. Measurements are carried out in two modes: with the near reactor on and off. As a result, it becomes possible to accurately measure the background and subtract it from the full spectrum when the power unit is running. A very pure spectrum of reactor antineutrinos is obtained. It is needed for the main research on the JUNO detector. At the same time, it is interesting to study the features of the spectrum and test different models suggested to describe it. To do this, the shape of the spectrum is fitted. At the same time, the dynamics of changes in the antineutrino counting rate is useful, which allows monitoring the operation of a nuclear reactor. The JINR group, together with Russian and European colleagues, implements an independent selection of IBD events, evaluation of its efficiency, determination of backgrounds, study of the reactor antineutrino spectrum and monitoring of the operating modes of the near power unit.

For 2027–2031, the plan is:

- precision measurement of the spectrum of reactor electron antineutrinos;
- accounting for contributions to the antineutrino signal from the second power unit and from the spent nuclear fuel pool, accounting for contribution from hot fuel in the reactor when it is shut down;
- investigation of the features of the measured antineutrino spectrum, including the study of an additional peak in the 4-6 MeV region (bump), the high-energy part of the spectrum (>8 MeV) and the possibility of describing the spectrum using different models (Huber-Mueller model, Kurchatov Institute model, summation model);
- obtaining the time dependence of the antineutrino counting rate in the detector and comparing the features of this dependence with various changes in the operation of the nuclear reactor;

- plotting time dependences of different backgrounds levels and identification of their connections or correlations with changes in the operation of the nuclear reactor or the TAO detector;
- determination of the sensitivity of the TAO detector to a change in the operating mode of the power unit or to its shutdown based on the observed antineutrino counting rate;
- estimation of the thermal power of the reactor with an accuracy of 1.5-2.0% based on the observed neutrino radiation; graph of changes in the thermal power of the power unit over time;
- evaluation of the component composition of nuclear reactor fuel based on the observed antineutrino counting rate and spectrum.

SiPM Power supply system

The SiPM power supply system of the TAO detector is a distributed multi-channel system that provides stable and individually adjustable high voltage for more than 4,000 SiPM matrices. The system includes VME power modules, control electronics, a CAN interface, and software integrated into the detector control system (DCS). Under conditions of long-term operation and limited accessibility of the equipment, the key requirements are high reliability, parameter stability, and full integration into the monitoring and control infrastructure.

In the period 2027–2031, the following activities are planned:

- production of additional spare components in case of failures;
- regular monitoring of power supply parameters (voltage, current, noise) and analysis of their long-term stability;
- identification of component degradation (DACs, power modules, cable infrastructure), analysis of channel failures, and their mitigation or compensation;
- maintenance of hardware infrastructure (VME crates, cabling system, transition boards, grounding);
- development of interfaces for interaction with the DCS and support of the API;
- ensuring stable synchronization of parameters with the central database and maintaining a history of changes;
- development and implementation of an alarm system for parameter deviations;
- further development of user interfaces (web-based GUI) for monitoring and control;
- visualization of channel status (maps, trends, time dependencies);
- automation of control operations (startup, shutdown, application of calibration corrections);
- development of recovery procedures and operational guidelines for shift personnel.

Calibration of SiPM

The calibration of SiPMs is a key element in ensuring a stable energy response of the TAO detector. Based on previously developed methods (including the analysis of single-photoelectron (SPE) spectra and the determination of SiPM parameters during mass testing), regular updates of calibration constants and monitoring of the uniformity of photodetector characteristics are required under long-term operation conditions. Although the TAO Silicon Photomultipliers have been extensively pre-characterized, further refinement of certain parameters is important for precise detector calibration. A series of measurements with SiPM matrices is scheduled to take place at DLNP, JINR.

In 2027–2031, the following activities are planned:

- using both radioactive sources and the LED system to perform comprehensive calibrations;
- regular gain calibration at the level of individual channels;
- monitoring of gain and breakdown voltage variations over time;

- adjustment of operating voltages (overvoltage) taking into account temperature and time-dependent effects;
- analysis of noise characteristics (dark count rate, optical crosstalk, afterpulsing) and their stability;
- optimization of operating parameters to achieve the best possible energy resolution;
- Upgrading of Test Benches for SiPM and Photodetector R&D at DLNP JINR;
- development of calibration data processing methods, including SPE spectrum fitting;
- automation of calibration procedures and integration of results into the Data Quality Monitoring (DQM) system.

TAO Data Quality System (TAO DQM, Data Quality Monitoring)

With the successful commissioning of the TAO detector, JINR is responsible for organizing quality control of the collected data. In practice, it is necessary to ensure the solution of two tasks.

The first task is the overall long-term monitoring of the sanity and stability of the measured values, such as the counting rate of single events, the counting rate of muons and other backgrounds, as well as monitoring the parameters of individual channels of the DAQ system, including their states, gains, dark noise (DCR), time bindings and offsets, SPE resolutions, trigger level and occupancy. The collected data is planned to be posted on a special website to facilitate their monitoring.

The second task is to validate runs. After each run, a pipeline of primary data processing will be started, allowing us to reconstruct the observed physical quantities, for example, the energy and coordinates of events in the detector. The quality, stability, and continuity of the data are the subjects of validation. It will be done by running a separate program and analyzing the output numbers, plots, and recommendations. Based on the results of the validation, a decision will be made whether the data in its current form can be used in physics analysis or needs to be reprocessed. In some cases, the data may be completely discarded.

For 2027–2031, the plan is:

- development of the website of the data quality monitoring;
- creating and updating lists of normally functioning channels of the DAQ (“good” channels), as well as lists of channels with any technical problems (“bad" channels);
- taking into account the prepared channel lists when converting data to the final esd format used in physics research;
- development and implementation of a full-fledged run validation program;
- formation and updating of run lists for use in various physics analyses.

JUNO veto system

The TT detector provides a more accurate measurement of cosmic muons trajectory compared to the CD and WP veto detector, though its efficiency is lower. However with the data from TT, the algorithms of the muons measurements in the CD and WP can be adjusted and improved. Also precise measurements of muon trajectories in CD and the reconstruction of the “IBD-like” events in the vicinity of the muon’s track will allow for studying of the background processes of Li9 and He8 cosmogenic production and can help with its suppression.

During the next period of the experiment, the TT data acquisition software created at JINR will be further improved as well as the detector's technical control programs (“slow control”) and the graphical user interface for the representation of reconstructed muons (“event display").

The efficiency of the muon tracks reconstruction in the TT detector depends on the properties of the detector itself and the algorithms of the data analysis. The main source of the TT signals is due to the natural radioactivity in the JUNO experimental hall which produces Compton electron hits in the TT strips. The first level trigger L1 doesn’t fully suppress this hit background, which leads to the

combinatorial background in muon detection. However one can try using modern Machine Learning approaches which can further improve efficiency and purity in muon reconstruction taking into account the available information on the TT hits as well as the data from WP and CD. Developing such algorithms and using them in data analysis will be a high priority task.

Intrinsic Scintillator Resolution and Detector Response

Analysis of JUNO calibration data shows that the detector's energy response model should be further improved. In particular, we need a more detailed description of the intrinsic liquid scintillator resolution. Preliminary studies indicate that this contribution can be at the 1.5% level.

In our detector response model, which was tested on laboratory data from several studies in the 10 keV to 4 MeV energy range, this contribution is taken into account directly.

In addition to the main data analysis method, we propose to develop a physically motivated approach. It is based on an analytical description of the response shape using the physical parameters of the detector. These parameters include: the relative spread of PMT sensitivities, the intrinsic resolution contribution, the mean relative variation of the PMT single-electron response, the fraction of the single-electron spectrum below the threshold, the mean charge remaining below the detection threshold, the PMT calibration correction, the relative variation of the mean PMT photon detection efficiency, and the additional relative signal variation for gamma quanta caused by the non-linearity of the scintillator response.

This approach uses observed values: the total charge and the number of fired PMTs. The response functions for these observables have an exact statistical description, which differs from a normal distribution. The width of the scintillation line, expressed in units of the corresponding estimator, is described by the parameters listed above. Depending on the reconstructed vertex, the estimator is corrected for its spatial position.

An additional advantage of this approach is an easier way to account for PMT dark hits. After converting the expected energy spectrum into one of the estimators, we simply need to convolve the resulting spectrum with a random sample. We expect that for energies up to ~5 MeV, the estimator based on the number of fired PMTs will provide better energy resolution. For energies above 5 MeV, the total collected charge will be a better choice.

For the analysis, we plan to use a joint multidimensional fit for both types of energy estimators. Having an overlapping energy range for both estimators will provide an additional cross-check for the model parameters and help to further improve the energy scale.

Computing and storage resources

JINR is one of the sites of the JUNO Distributed Computing Infrastructure (DCI), designed for data storage, processing and analysis. Within the DCI, JINR serves as a raw data center, a regional data storage center and a simulation center.

Raw data centers provide storage of backup copies of raw and reconstructed data, participate in their subsequent processing and provide computing resources integrated into the DCI. Regional storage centers host partial replicas of reconstructed data on disk resources and provide access to them for analysis and simulation jobs. Simulation centers provide computing resources for simulation and user analysis jobs and may also be involved in data reprocessing without the need for long-term storage of raw data.

The JINR computing infrastructure is based on the cloud infrastructure of the Multifunctional Information and Computing Complex (MICC) at the Meshcheryakov Laboratory of Information Technologies and is integrated into the DCI via grid interfaces and a batch system (HTCondor). This approach enables the deployment of dynamically configurable computing clusters and efficient redistribution of resources between different types of jobs.

The data storage system is organized as a two-tier architecture consisting of disk and tape layers. Disk storage is implemented using the dCache system and is used for data involved in current processing and analysis, providing efficient access within the grid infrastructure. Long-term storage and archiving are provided by a tape system based on EOS-CTA. According to the adopted storage model, active data from the last two years are stored on disk resources while older data are migrated to the tape archive.

The JINR infrastructure is integrated into the JUNO DCI via standard grid services that enable job execution and data access in a distributed environment. This approach ensures transparent use of computing and storage resources and scalability of the infrastructure as data volumes grow.

JUNO Data Quality

Validation of experimental data is one of the most important tasks. All subsequent processing of physical data is based on this. Data validation is divided into two subtasks: the first is determination of technical characteristics of photomultipliers during their operation (DCR, High Voltage, occupancy, time synchronization) and clarification of their selection criteria; the second is the validation of the experiment's physical data. Under conditions of long-term detector operation, selection criteria require refinement. Each dataset may have its own features that need to be taken into account. In 2025-2026, a session validation monitoring system was developed for the JUNO experiment with a graphical interface, and data collected during the first six months of data taking were validated.

In 2027–2031, the following is planned:

- Participation in the development of the offline data monitoring system (ODM);
- Integration of the Run Validation and Channel Quality subsystems into the offline data monitoring system (ODM);
- Expansion of the Channel Quality subsystem by adding supplemental tag sets for all detectors;
- Integration with the JUNO distributed information-computing environment (DICE);
- Verification of characteristics and refinement of selection criteria for the quality of large and small photomultipliers for each physical dataset;
- Participation in the validation of physical data throughout the entire data-taking period of the experiment;
- Participation in research on specific technical features of photomultipliers (flashers).

Muon event reconstruction

We have developed a new method for reconstructing muon tracks using spherical harmonic expansion. In this case we can describe a signal from muon track that passed through the detector with a limited number of parameters which is much less than the number of PMTs and in that way we can speed up our reconstruction procedure. We are using the following reconstruction procedure:

- simulation of reference muons: vertical muons with step 0.5 m along Ox-axis;
- making dependence of detector response snapshots for muon tracks on distance;
- making detector response snapshot for muon track that should be reconstructed;
- rotating reference muons while the signal from the detector from input muon will not be the same as for the reference muon;
- found rotation angles — direction of incoming muon track.

With this method it is possible to reconstruct single and multiple muon tracks by the sum of spherical functions from different muon tracks. Rotation of calibration muons and muon track parameters are defined with the chi-square functional.

Muon track reconstruction procedure with the help of spherical functions has the following advantages:

- information from the PMTs is collecting during 300 ns (only first hit in other methods) which is safe from the noise and PMTs inefficiency, because noise signal is distributed uniformly on the sphere and compensated by the calibration coefficient during the fit;
- existence of other signals does not have a big influence on reconstruction quality;
- this method allows us to apply different muon track combinations for one event for multiple muon track reconstruction;
- with this method we can reconstruct the electromagnetic shower produced by the muon interactions with the scintillator.

Event selection and statistical oscillation analysis

Inverse beta decay is detected via the coincidence of two signals (scintillation flashes): a prompt signal from a positron, whose energy is proportional to the neutrino energy, and a delayed signal from a gamma ray with a fixed energy of 2.2 MeV following neutron capture on hydrogen. This delayed signal serves as a tag, allowing for a significant suppression of background contributions. Background sources include radioactive accidental coincidences, long-lived ^{9}Li/^{8}He (β-n decay), geoneutrinos, and neutrinos from other nuclear power plants worldwide, among others. A distinguishing feature of JUNO compared to previous detectors is its immense scale, featuring a fiducial volume radius of 17.2 meters. Consequently, all stages of event analysis are complicated by the necessity to account for the detector's large dimensions and non-uniformity. The JINR group has implemented an independent IBD event selection, along with an evaluation of the detection efficiency and the accidental coincidence background.

The JINR group is one of the key teams within the JUNO collaboration, responsible for the statistical analysis of reactor antineutrino data. We have developed two frameworks for model building and statistical analysis: GNA[19] (Global Neutrino Analysis, C++/Python) and dag-modelling[20] (Python/Numba). These frameworks serve as the foundation for the reactor antineutrino oscillation analysis conducted by the JINR group in both the JUNO and Daya Bay experiments. The GNA project has been extended to support both accelerator[21] and atmospheric neutrino experiments. Notably, GNA was employed in parallel analyses to derive the final results of the Daya Bay experiment[22], to evaluate the sensitivity of the JUNO experiment[23] in its configuration with the TAO near detector, and to obtain the first JUNO results[24]. Furthermore, utilizing the dag-modelling framework, we created an open model of the Daya Bay experiment[25]. This model fully replicates the statistical oscillation analysis using the complete public Daya Bay dataset[26], which was also prepared by our group.

Both frameworks feature computationally efficient implementations of the JUNO and Daya Bay experiment models, alongside tools for minimization and statistical evaluation. The dag-modelling project is an evolution of GNA; moving forward, the analysis will be fully migrated to it, and the development of GNA will be discontinued.

Future work entails the advancement of statistical analysis methods, as well as the continued development and maintenance of software solutions, encompassing the following tasks:

- Analysis Support and Development:

[19] https://git.jinr.ru/gna/gna, https://arxiv.org/abs/1903.05567
[20] https://github.com/dagflow-team/dag-modelling
[21] Physics of Particles and Nuclei Letters volume 19
[22] https://arxiv.org/abs/2211.14988
[23] https://doi.org/10.1088/1674-1137/ad7f3e
[24] https://arxiv.org/abs/2511.14593
[25] https://github.com/dagflow-team/dayabay-model
[26] https://zenodo.org/records/17587229

    - Maintaining up-to-date data on JUNO and TAO detector performance and background contributions..
    - Performing a joint statistical analysis of data from the JUNO and TAO detectors, along with the Daya Bay experiment. This includes the simultaneous analysis of multiple data-taking periods in JUNO, incorporating data from different JUNO shells (to account for non-uniformity), and utilizing different virtual TAO sub-detectors (to account for oscillation effects at varying baselines).
    - Evaluating the measurement uncertainties of the oscillation parameter Δm^2_{31} using the Feldman-Cousins method.
    - Study of signals from “new physics”: non-standard interactions, neutrino decays, etc.
    - Providing long-term support for the Daya Bay model.
- Conducting Physical Measurements:
    - Measuring the neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} и $\sin^2 2\theta_{12}$ in JUNO.
    - Determining the neutrino mass ordering in JUNO.
    - Measuring the reactor antineutrino spectrum in TAO.
    - Performing the first search for sterile neutrino oscillations in TAO data.
    - Searching for new physics in TAO data.
- High-Performance Computing Support in dag-modelling:
    - Implementing support for GPU-accelerated computing.
    - Integrating automatic differentiation
    - Optimizing existing algorithms

Atmospheric neutrino data analysis

Although JUNO is a liquid scintillator detector, it nonetheless has directional sensitivity to high-energy muons and electrons, achieving an angular resolution of approximately 10° for energies above 2.5 GeV. This capability enables the selection of the upward-going flux of high-energy particles, specifically, those originating from muon and electron neutrinos traversing the Earth. The presence of the Earth's matter effect distinctly distorts the oscillation probabilities for neutrinos with energies around 5 GeV that pass through the Earth's core ($\cos\theta<=0.8$). This distortion is most pronounced for muon and electron neutrinos under the Normal Mass Ordering (NO) hypothesis, and for muon and electron antineutrinos under the Inverted Mass Ordering (IO) hypothesis. Consequently, JUNO has the potential to determine the neutrino mass ordering (NMO) using atmospheric neutrinos.

Furthermore, since mass ordering manifests itself differently in the spectra of atmospheric and reactor neutrinos, joint data fitting will result in a synergistic increase in sensitivity compared to a simple statistical combination.

The JINR group has established expertise in statistical analysis and sensitivity evaluation for atmospheric neutrinos, alongside a ready-to-use infrastructure for conducting joint analyses. Future work entails active participation in atmospheric data analysis, specifically encompassing the following tasks:

- developing particle identification algorithms (ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$);
- reconstruction of neutrino directions using techniques developed for reconstructing muon tracks;
- performing statistical data analysis to measure neutrino oscillation parameters and determine the mass ordering;
- evaluating JUNO's joint sensitivity to the mass ordering using combined reactor and atmospheric neutrino samples;
- conducting the final joint statistical analysis of reactor and atmospheric neutrino data to robustly determine the neutrino mass ordering.

Additional Physics Research

At present, the group's efforts and plans are primarily focused on the analysis of reactor neutrino data and, secondarily, on atmospheric neutrino data. Nevertheless, with an anticipated influx of new students and PhD candidates, particularly during the second half of the project, additional research tasks may be considered.

Expected results (2027-2031)

1. Detector Energy Scale and Intrinsic Resolution:
    a. extracting the necessary parameters from calibration data and Monte Carlo (MC) simulations;
    b. tuning the standard simulation code to account for intrinsic resolution and calibration data;
    c. incorporating the analytical method into the standard data-fitting framework.
2. Muon Track Reconstruction:
    a. verifying the quality of muon track reconstruction using the muon veto system;
    b. utilizing the water veto to better constrain the initial conditions for muon track fitting;
    c. performing joint muon reconstruction using the central detector, the water veto, and the muon veto;
    d. optimizing the speed of muon track reconstruction;
    e. integrating of a new reconstruction method into the main program of reconstruction of events;
3. Long-Baseline Reactor Electron Antineutrino Oscillations in JUNO:
    a. determining the neutrino mass ordering;
    b. precision measurement of the neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{31}.
4. Measuring the geoneutrino flux from ^{238}U and ^{232}Th.
5. Short-Baseline Reactor Electron Antineutrinos in TAO:
    a. precision measurement of the reactor electron antineutrino spectrum;
    b. placing constraints on the sterile neutrino oscillation parameters $\sin^2 2\theta_{14}$ and Δm^2_{41}.
    c. phenomenological studies (searching for and setting limits on parameters of):
        i. neutrino decay;
        ii. non-standard interactions (NSI).
6. Atmospheric Neutrinos in JUNO:
    a. Measuring the flux and spectrum of atmospheric neutrinos in JUNO;
    b. First observation of atmospheric neutrino oscillations in a liquid scintillator detector;
    c. Determining the neutrino mass ordering using atmospheric neutrinos.
7. Joint Data Analysis:
    a. Determining the neutrino mass ordering through a combined analysis of reactor and atmospheric (anti)neutrino data within the JUNO detector;
    b. Determining the neutrino mass ordering via a joint analysis of JUNO data alongside long-baseline accelerator and atmospheric experiments.

Justification of financial requests

To carry out research and methodological work on photodetectors and to upgrade the laboratory's technical facilities, instrumentation and control equipment will be purchased at a cost of $50,000 per year. Additionally, there are plans to upgrade the DAQ servers for the Top Tracker, for which JINR is responsible, at a cost of $25,000.

To maintain the operation of the TAO detector, $20,000 per year will be required for the procurement of components and the production of spare parts and power boards needed in the event of SiPM power module failures. Within this budget, calibration light sources for TAO will also be purchased and manufactured.

We plan purchasing computing servers. According to MoU during the project time frame JINR is expected to acquire computing servers with 4000 CPU cores. In this project we include the purchase of servers with 200 CPU cores of cost of $200,000 each year. The purchase of servers beyond this amount will be carried out within the "Neutrino computing platform", also after clarification of the amount of servers required as the data is collected. The development of the JUNO cluster is a valuable part of the development of "Neutrino computing platform" of JINR, as the resources, which are at the moment not involved in the JUNO tasks, are shared to the all the users of the platform.

Regular ISTC (International Scientific and Technical Cooperation) costs include the operational fee, travel for data-taking shifts, collaboration meetings, and conferences. The operational fee for the JUNO experiment amounts to $120,000 per year. JINR is required to participate in a total of 4 months of shifts[27], with associated costs estimated at $45,000 per year. Travel expenses for collaboration meetings (held twice a year) and scientific conferences are estimated at $40,000 and $70,000, respectively. In total, the aforementioned regular expenses amount to $275,000 per year.

SWOT-Analysis

	Helpful	Harmful
Internal	**STRENGTHS** ● Determining the neutrino mass ordering using a method distinct from other experiments. ● Precision measurement of neutrino oscillation parameters. ● Geoneutrino measurements. ● Exploring other neutrino physics (solar, atmospheric, etc.). ● JINR's crucial responsibilities for two major subsystems: the High Voltage (HV) power supply for PMTs and the power supply for SiPMs; ensuring the mass testing of PMTs and SiPMs; and contributing to the VETO system. ● JINR plays a leading role in data analysis.	**WEAKNESSES** ● Insufficient structural or detector integrity. ● Insufficient reliability of the electronics or power supply systems.
External	**OPPORTUNITIES** ● Discovering Physics Beyond the Standard Model (BSM). ● Observation of a supernova burst. ● Detection of the Diffuse Supernova Neutrino Background (DSNB). ● Reduction of systematic uncertainties through new measurements or theoretical advancements.	**THREATS** ● A major accident or catastrophic failure. ● Inability to reach an agreement with other collaborations regarding joint data analysis.

[27] one of 3 shifts per day

	● Development of new methods and technologies. ● Collaboration with Chinese institutes and joint funding opportunities.	

Launched in late 2025, the JUNO experiment represents a massive leap forward in both scale and precision among reactor neutrino and liquid scintillator experiments. The JUNO detector is 20 times larger than KamLAND, which is currently the largest reactor antineutrino detector. The experiment's operational requirements mandate maximum geometric PMT coverage and an energy resolution of approximately σ=3% at 1 MeV of deposited energy. Consequently, the detector's design introduces several technical challenges, imposing stringent requirements on reliability and safety. Potential risks have been minimized through rigorous subsystem testing and by enforcing strict reliability standards for the detector's components and electronics.

Conducting a joint analysis with other experiments is a lengthy process that requires careful coordination at the collaboration level, an agreement which, naturally, has not yet been finalized at the time of this proposal's preparation. However, the project authors consider the risk of an unfavorable outcome to be minimal, as all parties share a strong interest in joint analyses. Furthermore, there is a proven positive track record of such collaborative studies, both involving our team (e.g., Daya Bay/MINOS/Bugey; JUNO/KM3NeT/ORCA sensitivities) and within the accelerator neutrino community (e.g., NOvA/T2K).

2.3. Estimated completion date

The project is scheduled for completion in 2045

2.4. Participating JINR laboratories

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	10380	16640	22900	29170	35430
Tier 1 (core-hour)					
Tier 2 (core-hour)					
SC Talker (core-hour) - CPU - GPU					
Clouds (CPU cores)	6300	6300	6300	6300	6300

In addition to the estimates presented in the table, a dedicated disk storage system based on dCache is used. According to the adopted storage model, active data from the last two years are stored

on disk resources while older data are migrated to the tape archive. Starting from 2027, based on current estimates, the required disk resources amount to about 6.5 PB and are expected to remain approximately at this level.

2.5. Participating countries, scientific and educational organisations

Organisation	Country	City	Participants	Type of agreement
IHEP	China	Beijing	Yifang Wang +10	MoU
SJTU	China	Shanghai	Jianglai Liu +10	MoU
SYSU	China	Guangzhou	Wei Wang +10	MoU
INFN	Italy	Catania, Rome, Padova	Giuseppe Andronico +1 Stefano Maria Mari +1 Alberto Garfagnini +5	MoU MoU MoU
GSI	Germany	Darmstadt	Livia Ludhova +10	MoU
EKUT	Germany	Tuebingen	Tobias Lachenmeier +1	MoU

2.6. Co-executing organisations *(those collaborating organisations/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).*

IHEP, SYSU, JINR

3. Staffing

3.1. Staffing needs in the first year of implementation (total number of participants)

№№ n/a	Category employee	Core staff Amount of FTE	Associated Personnel Amount of FTE
1.	scientific staff	10.9	1.5
2.	engineers	7.1	1
3.	professionals	—	—
4.	employees	—	—
5.	workers	—	—
Total:		**18**	**2.5**

3.2. Human resources available

3.2.1. JINR core staff (total number of participants)

№№ п/а	Category of employees	Division	Position	Amount of FTE
1.	scientific staff	DLNP	junior researcher, research intern	3.4

			researcher	4.4
			leading/senior researcher, head of a sector	2.8
		VBLHEP	senior researcher	0.3
2.	engineers	DLNP	electronics engineer, engineer, leading engineer, leading electronic engineer, senior engineer	4.1
		MLIT	engineer-programmer, leading programmer, research intern, laborant	3
3.	professionals	—	—	—
4.	workers	—	—	—
Total:				**18**

3.2.2. JINR associated personnel (total number of participants)

№№ п/а	Category of employees	Partner organisation	Amount of FTE
1.	scientific staff	MSU	1.3
		INR	0.5
2.	engineers	MSU	0.6
		INR	0.5
3.	professionals	—	—
4.	workers	—	—
Total:			**2.9**

4. Financial support

4.1. Total estimated cost of the project

$2,750.

4.2. Extrabudgetary funding sources

None.

Project Leader _____/_____/

Date of submission of the project to DSOA: _____

Date of decision of the laboratory's STC: _____ document number: _____

Year of the project opening: _____

(for renewable projects) − Project start year: _____

Schedule proposal and resources required for the implementation of the Project

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)	1375	275	275	275	275	275
		Materials	100	20	20	20	20	20
		Equipment and third-party services (commissioning)	1250	250	250	250	250	250
		Commissioning work	—	—	—	—	—	—
		Services of research organisations	—	—	—	—	—	—
		Acquisition of software	—	—	—	—	—	—
		Design/construction	—	—	—	—	—	—
		Service costs (*planned in case of direct project affiliation)*	—	—	—	—	—	—
Resources required	**Norm-hours**	Resources						
		−the amount of FTE,	90	18	18	18	18	18
		−accelerator/installation,	—	—	—	—	—	—
		−reactor,….	—	—	—	—	—	—
Sources of funding	**Budgetary resources**	JINR budget *(budget items)*	2725	545	545	545	545	545
	Extrabudgetary (esupplementary estimates)	Contributions by co-contractors	—	—	—	—	—	—
		Funds under contracts with customers	—	—	—	—	—	—
		Other sources of funding	—	—	—	—	—	—

Project Leader _____/_____/
Laboratory Economist _____/_____/

APPROVAL SHEET FOR PROJECT

Study of neutrino oscillations in the JUNO experiment (participation of JINR)

SHORT NAME OF THE PROJECT: JUNO

PROJECT CODE: 02-2-1099-1-2010/2031

THEME CODE: 02-2-1099-2010

PROJECT LEADER: D. V. Naumov

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

Annex 4.
Project report form

APPROVED
Director of Laboratory
_____/_____/
"_____"_____ 2026

REPORT ON PROJECT
IN FIELD OF RESEARCH WITHIN
THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the Project
1.1. Scientific field particle physics

1.2. Name of the Project Study of neutrino oscillations in the JUNO experiment (participation of JINR)

1.3. Project code 02-2-1099-2010/2026

1.4. Theme code 02-2-1099-2010

1.5. Actual duration of the Project 2026

1.6. Project Leader(s) D.V. Naumov

2. Scientific report

2.1. Annotation

The 2023−2026 period was pivotal in the preparation of the JUNO experiment. It includes the stages of construction and commissioning of both the JUNO detector and TAO detector, collection of the first physical data and the publication of the first physics result — measurement of two neutrino oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$ with the best precision.

JINR plays a major role in all the stages of the experiment, including construction, operation and data analysis. The contribution in the reported period includes:

(i) The high voltage units for all the JUNO large (20 inches) and small (3 inches) photomultipliers (PMTs) with an overall amount exceeding 25 thousand units were installed. JINR is responsible for design and production of the units;

(ii) JINR contributed to the construction of the JUNO detector;

(iii) JINR contributed to the construction of the Top Tracker (TT) detector by developing a mechanical support system, hardware and software for monitoring of T scintillators, tracks reconstruction and data acquisition system (DAQ);

(iv) Mass tests and commissioning of large PMTs;

(v) JINR contributed to the design and construction of JUNO's near detector — TAO: procurement of half of 4100 tiles (130k dices) of silicon photomultipliers (SiPM) and their

mass-testing, production and operation of SiPM power supply system (4100 channels);

(vi) JINR maintains a dedicated data center for the simulation, storage, and processing of JUNO experiment data. The JINR facility operates as one of the three European data centers supporting JUNO's computing needs.

(vii) JINR actively contributes to software development. This includes the creation of the Global Neutrino Analysis (GNA) and dag-modelling frameworks for statistical oscillation analysis, the development of event reconstruction and data analysis algorithms, and the implementation of a Data Quality Monitoring (DQM) service;

(viii) JINR directly participates in the processing and analysis of the data, from data quality and to event selection and statistical analysis.

2.2. A detailed scientific report

2.2.3. A description of the scientific work undertaken and the results obtained.

Muon track reconstruction

A program was written to calculate the synchronization time of muon triggers between three detectors: the central detector, the water pool, and the top tracker. The following values were found: Tcd − Twp ∼ −75 ± 250 ns, Tcd − Ttt ∼ 285 ± 250 ns (see Fig. 1).

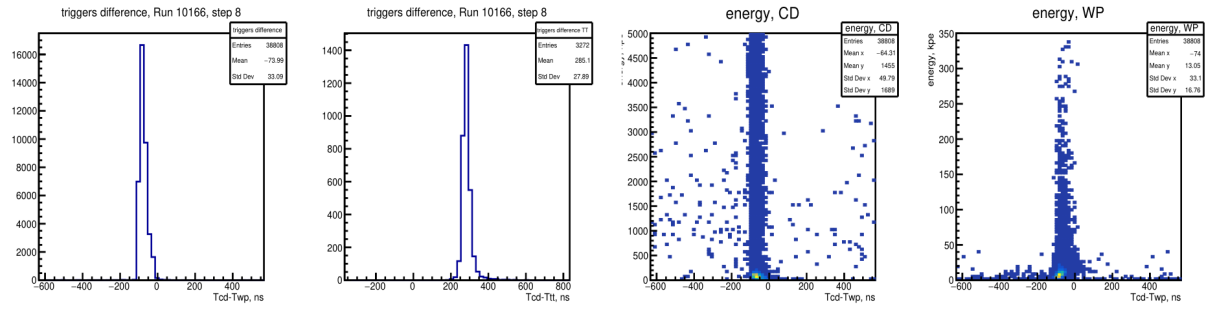


Figure 1. Time between triggers Tcd − Twp and Tcd − Ttt.

The following resolution was obtained during the reconstruction of muon tracks: the distance and angle between the simulated and reconstructed muon tracks are 32 cm and 1.16 degrees. The average volume lost when cutting out the muon track (without taking into account Li9/He8 isotopes production) is 0.045% (see Fig. 2).

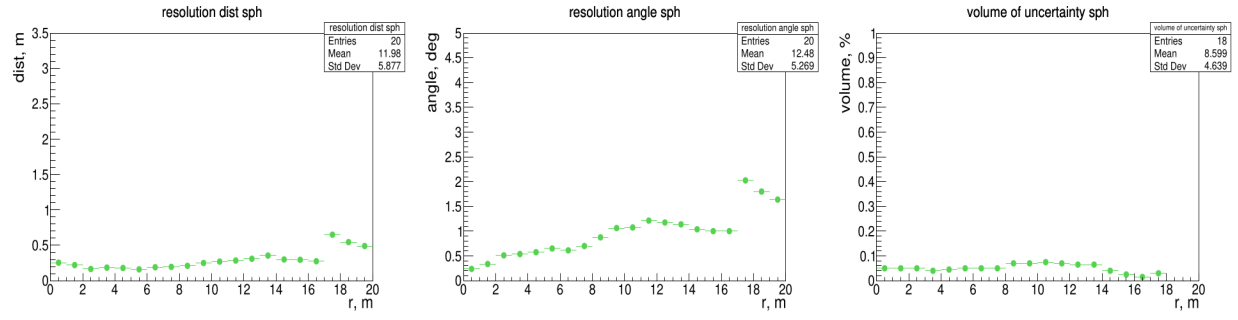


Figure 2. Distance and angle between the simulated and reconstructed muon tracks. Average volume lost when cutting out the muon track.

The classification efficiency of muon events is 95.3%. If the distance between muon tracks is less than 8 meters, the probability of identifying the event as a two-track event is 50% (see Fig. 3).

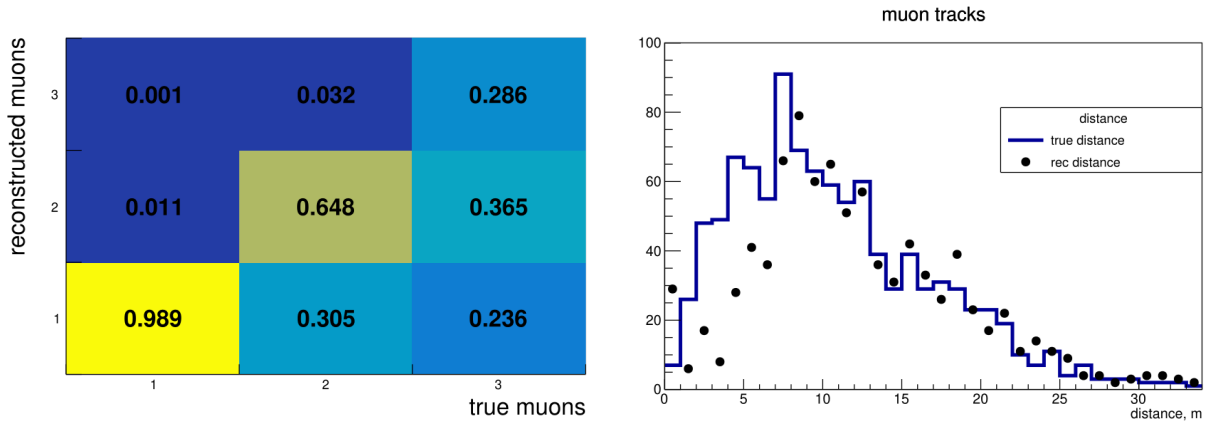


Figure 3. Classification efficiency of muon events and the distance between two muon tracks for simulated and reconstructed events.

Large PMTs and HV units (2024)

The Central Detector (CD) of the JUNO experiment is a spherical acrylic vessel with a diameter of 35 m, filled with 20 thousand tonnes of liquid scintillator. The detection of scintillation light is performed using approximately 20,000 20-inch photomultiplier tubes (PMTs), including 17,612 PMTs of the central detector and 2,748 PMTs of the VETO system, as well as about 26,000 3-inch PMTs. This configuration provides a coverage of approximately 78%.

The installation of the 20-inch PMTs was carried out over a period exceeding two years, from October 2022 to December 2024. In total, 20,343 PMTs were successfully installed. During the installation campaign, seven PMT testing campaigns were conducted, covering approximately 19,800 devices; the remaining PMTs were installed and tested at the final stage of the work.

As part of the detector preparation, more than 25,000 High-Voltage Units (HVUs) were produced to supply power to the PMTs. These modules were installed in the JUNO detector together with the underwater electronics and connected to the PMTs. Approximately 1,600 HVU channels were used to power the 3-inch PMTs.

Firmware upgrades of the HVU were implemented, and dedicated software was developed for in-situ verification of PMT operability during installation. All PMTs underwent pre-installation testing at the Pan-Asia facility and were subsequently transported to the JUNO experimental site. Prior to installation into the detector, each PMT was connected to a high-voltage source, and its noise level was measured under dark conditions. A slight reduction in the noise level was observed, attributed to PMT relaxation after prolonged storage in complete darkness.

During installation, prompt verification of the correctness of electrical connections was required. An algorithm was implemented in the HVU software to enable testing at reduced high voltage under low ambient light conditions. The method is based on the measurement of photocurrent on top of the intrinsic idle current of the HVU, allowing reliable identification of electrical contact and channel operability.

For the main tests, fully dark conditions were required. To achieve this, all sources of visible light in the experimental hall, supporting structures, and adjacent rooms and tunnels were switched off. The ambient light level was monitored using a dedicated reference PMT; the testing procedure was initiated once the acceptable dark count rate threshold was reached.

High voltage was applied to the PMTs in a stepwise manner (0 V → 800 V → 1200 V → 1600 V → operating voltage), with stabilization time at each step and measurement of the dark current. This approach minimized the risk of PMT damage associated with residual illumination, instability during

initial power-up, or installation defects. At the final stage, the voltage was set according to calibration corresponding to a gain of 10^7, and measurements were performed over several hours under dark-noise conditions. In addition to the dark count rate, the waveform shapes of noise pulses were recorded.

PMT signals were digitized using ADCs, and preliminary data processing was performed in FPGAs integrated into the Global Control Unit (GCU) modules. The HVU power system was controlled via the Detector Control System (DCS), while data acquisition was carried out using backend electronics. The entire system provided continuous monitoring of PMT parameters during testing.

Due to the complexity of installation conditions and the requirement for complete darkness, testing was predominantly performed during nighttime. Preparation for each test required several hours, including additional verification of the absence of stray light, which limited the measurement frequency.

Researchers from JINR participated in the development of the HVU software, testing of the HVU system, and in the activities of the PMT instrumentation consortium during these operations.

Filling and Commissioning of JUNO (Late 2024 – Early 2025)

The assembly of the central detector, including the installation and connection of photodetectors, the construction of the acrylic sphere, and the installation of the Earth's magnetic field compensation coil, took place in 2024. Structural work, carried out with the direct participation of DLNP JINR staff, was completed in December, after which the filling and commissioning of the detector commenced. Filling the pool and the central detector with ultra-pure water took two months. Starting in February 2025, the water in the central detector was gradually displaced by the liquid scintillator (LS). Simultaneously, the high-voltage (HV) power supply was turned on, and continuous data taking began. Full-scale shift operations at the detector also started at this time. The LS filling process took nearly seven months, concluding in August. Subsequently, data collected following a one-week calibration campaign were directly utilized for physics analysis [1].

A total of 20348 twenty-inch photomultiplier tubes (PMTs) were installed and commissioned in JUNO during the liquid scintillator filling phase to study their performance and initiate the detector's commissioning. It has been established that, to date, 19872 of them are operating normally, 454 intermittently produce flashes (acting as "flasher" PMTs) that hinder operation, and 22 are completely non-functional. Thus, the current overall failure rate attributed to the PMTs and their HV power supplies is ~0.11%, which aligns with the target parameters set during the JUNO design phase.

The detector response was investigated, and it was shown [2] that the key performance indicators are in good agreement with expectations. Based on measurements of ^{214}Po alpha decays, the energy reconstruction is spatially uniform to within 1% (see Fig. 4) inside a sphere with a radius of 16.5 m (the fiducial volume). The energy scale non-linearity was measured with an accuracy better than 1% using gamma-emitting calibration sources. Using data from these same calibration sources, the achieved energy resolution is σ=3.4% at 1 MeV (see Fig. 5) at the detector center (which is currently worse than the design goal of ~3%).

The excess in resolution width over the design value is consistent with the expected contribution from the intrinsic scintillator resolution of 1.5% (added in quadrature) [15, 22], which was not accounted for in the initial design.

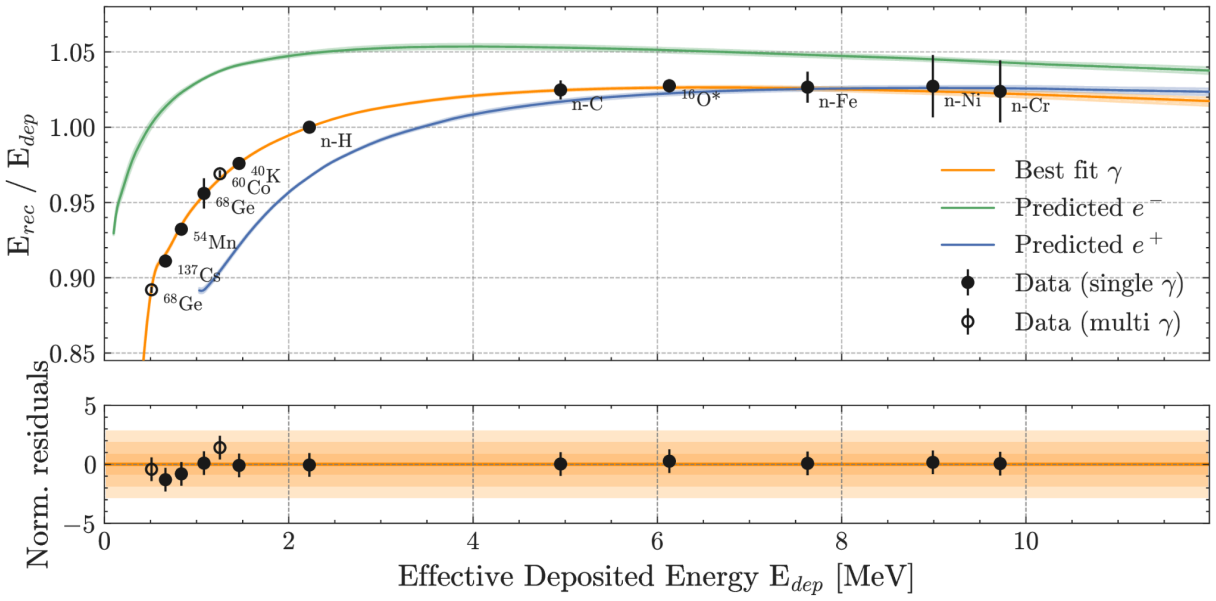


Figure 4. JUNO energy scale as a function of energy measured with γ sources placed at the CD center.

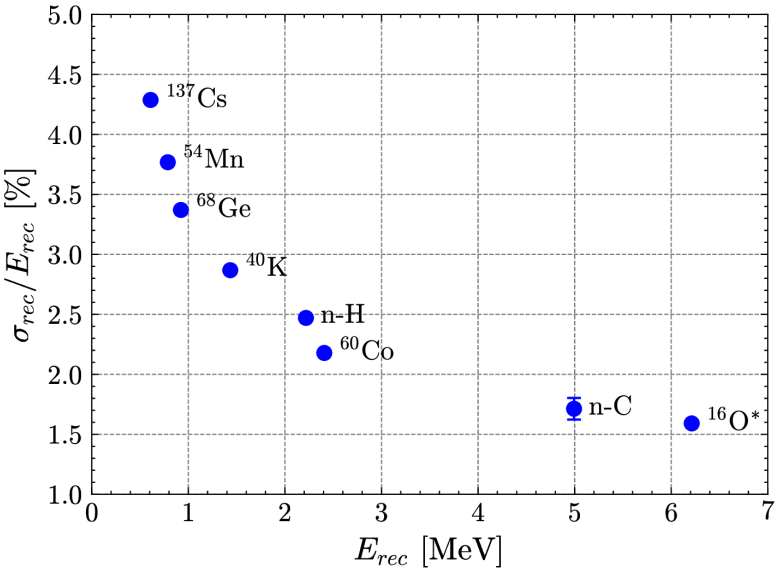


Figure 5. JUNO energy resolution as a function of energy measured with γ sources placed at the CD center.

Veto TT

The Top Tracker (TT) detector, which is a part of the JUNO Veto system, has three layers of coordinate strip detectors, it is installed above the central detector (CD) and covers about 1000m2. The main task of TT is to refine the trajectory of muons entering the CD in order to exclude background events generated by them difficult to distinguish from the IBD signal.

TT was created from the scintillation modules of the OPERA detector, dismantled in 2015 and transported to China in 2017. Taking into account the age of the plastic scintillator (the main batch was

produced in 2004-2005), the complex logistics of its delivery to China and the conditions of its subsequent storage, a system for monitoring the condition of TT modules in containers was created. The mobile data acquisition system available for some of the modules made it possible to register cosmic muons and monitor the TT signals from them. The system allowed us to evaluate the change in the characteristics of the scintillator before its assembly in JUNO, the drop in light output since manufacture was estimated as about 30%.

The TT detector was assembled and installed from January to June 2025, after the assembly and launch of all other JUNO systems. JINR has developed a mechanical TT detector support system (the total weight is ~100 tons), the manufacturing order for which was placed in China. The JINR team participated in all stages of the TT assembly: the installation of mechanical support, the cabling of the detector, the assembly and installation of the TT detection elements themselves. The general appearance of the TT after assembly is shown in Figure 6. The observed distributions of muon directions are shown in Figure 7.

JINR has developed software for collecting TT detector data and integrating it into the data stream from other JUNO detectors. Currently, the new TT electronics have not yet been fully launched, in particular, there is no second-level trigger, so the data acquisition system is adapted to this mode and the TT data is saved for full analysis offline. To use TT data in online analysis, along with data from other JUNO systems, they need to be crosslinked in time. For this purpose, the data stream is ordered by time in each transmission portion. At the current stage, the priority is to effectively save and transfer information from TT. In the future, it is expected to optimize the data flow and reduce its volume.

Given the aging of the scintillator and the limited number of detector layers in the TT, a joint analysis of data from CD, ICP and TT is needed to effectively detect muons.

Work is currently underway to assemble additional detectors based on RPC technology to expand the TT area and more efficiently detect muons entering the Central Detector. Algorithms for the combined reconstruction of muon tracks at JUNO are currently under development.

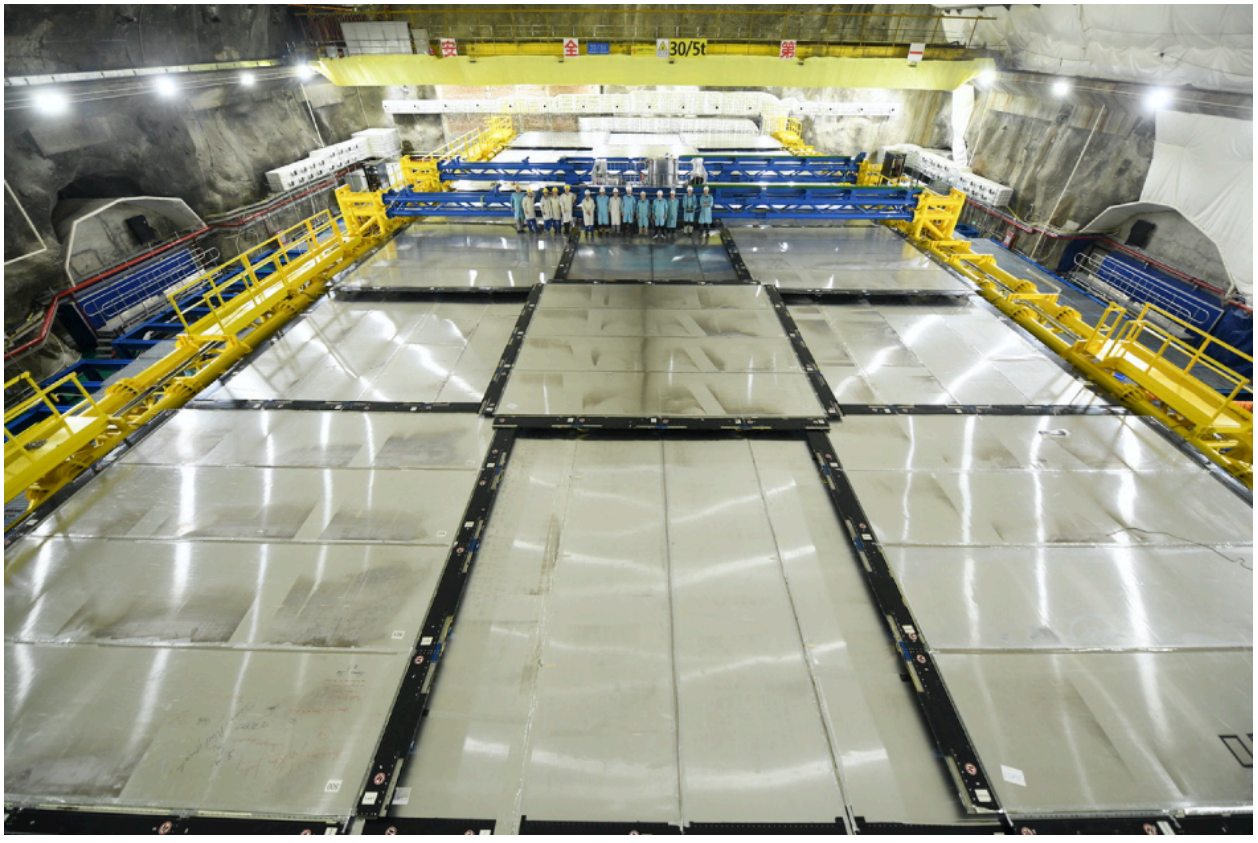


Figure 6. General view of the Top Tracker detector after its installation in JUNO experimental hall.

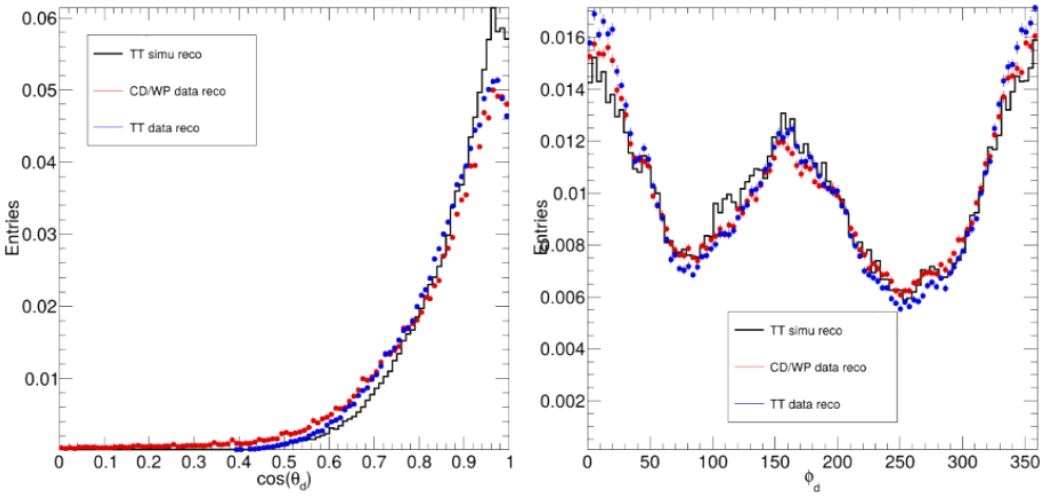


Figure 7. Comparison of the angular distribution of the cosmic muons registered by TT, CD, WP detectors with the simulation.

TAO

Mass testing

Mass testing of SiPMs for the TAO experiment was carried out in 2024–2025. Approximately 4,100 matrices (tiles) were characterized, corresponding to about 130,000 SiPMs operating at a temperature of −50 °C. The main objective was to ensure quality control and uniformity of photodetector parameters, including photon detection efficiency (PDE), gain, optical crosstalk, and dark count rate (DCR).

At the first stage, a visual inspection of the tiles was performed to identify defects in the epoxy coating. Subsequently, a dedicated mass-testing setup was developed and commissioned, enabling simultaneous measurements of 16 tiles (one SiPM channel per matrix) [19]. In accordance with the TAO detector configuration, SiPMs were paired into a single readout channel, resulting in a total of approximately 65,000 channels to be measured. Each channel was powered individually, allowing precise voltage control and current measurements. Using multiplexers, sequential channel switching was implemented, enabling measurements of all SiPMs on 16 matrices. A full measurement cycle took about 1.5 hours, and up to 4 hours including cooling and heating.

To ensure uniform illumination, a stabilized LED light source combined with an optical fiber splitter was used. Light was delivered to each tile via fibers equipped with diffusers, while reference SiPMs located near the tiles were used to monitor light intensity and calibrate the light field. Scanning of the light distribution was performed using a movable platform with stepper motors. For each position, up to ~3×10^4 events per channel were recorded, providing a statistical precision better than 1%. Light field measurements were performed twice daily—before and after the main measurements.

A data acquisition and control system based on a client–server architecture was developed and implemented. This enabled automation of the measurement process, real-time monitoring of parameters, and integration of all system components. Data processing was performed on a computing

cluster, with subsequent extraction of SiPM parameters from charge spectra and signal waveform analysis.

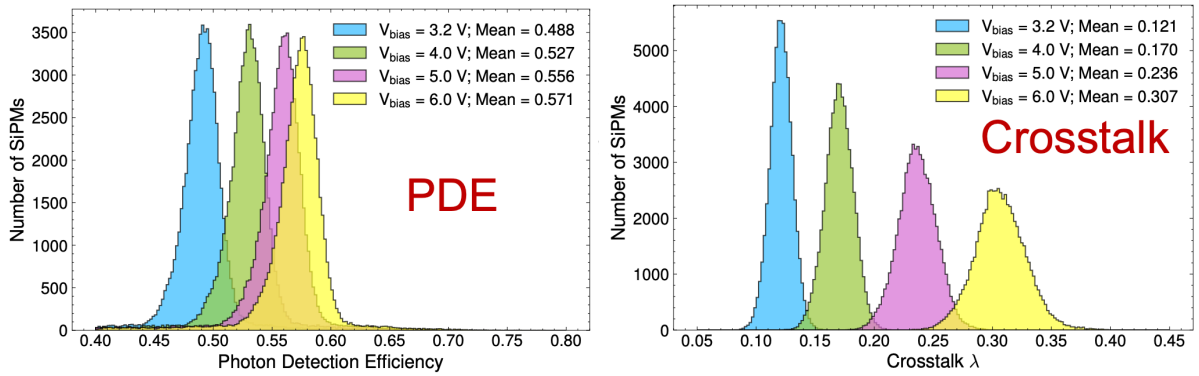


Figure 8**.** Distributions of photon detection efficiency (PDE) (left) and optical crosstalk (right), and their dependence on SiPM overvoltage.

During operation of the setup, the stability of the light flux was demonstrated to be better than 1%. The measurements allowed determination of the main SiPM characteristics, including gain, PDE, optical crosstalk, dark current, and dark count rate (DCR). The obtained parameter values are within the expected range: PDE at the level of ~60%, crosstalk around 25% [18], and low DCR values at the operating temperature of −50 °C. The breakdown voltage for each SiPM was determined from the gain–voltage dependence.

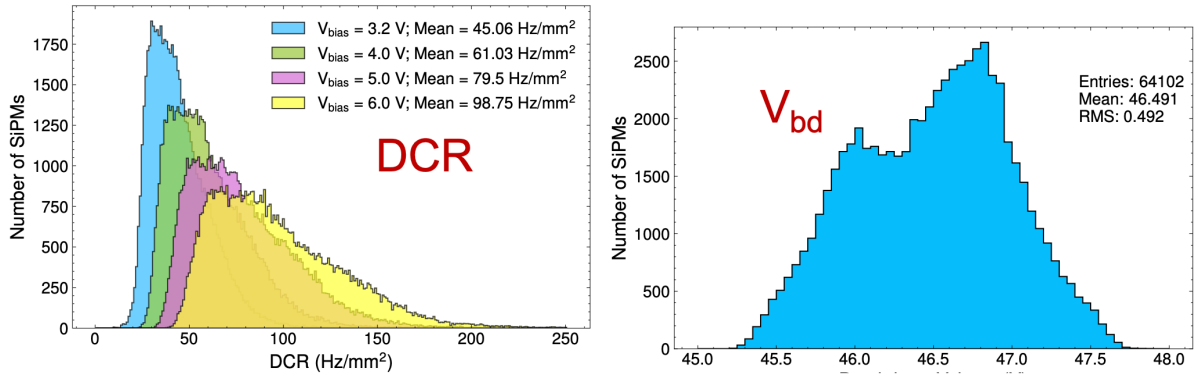


Figure 9. Distributions of the dark count rate (DCR) and its dependence on SiPM overvoltage (left), and the distribution of breakdown voltage (right).

In addition, the temperature dependence of SiPM noise was studied, allowing the extraction of the activation energy. This made it possible to estimate SiPM aging processes under operating conditions at −50 °C. For accelerated degradation testing, SiPMs were biased for two weeks at room temperature, enabling extrapolation of detector behavior to long-term operation [17].

Figures 8 and 9 show the distributions of PDE, crosstalk, and dark count rate (DCR) for all measured SiPM channels, as well as their dependence on overvoltage. It is shown that increasing overvoltage leads to higher PDE and improved light collection. However, this is accompanied by increased crosstalk and noise, which degrades the energy resolution. Therefore, an optimal overvoltage value exists, providing a balance between detection efficiency and noise level.

Based on the obtained results, the detector energy resolution was estimated (see Fig. 10), taking into account contributions from both the scintillator and photodetectors, as well as its dependence on

SiPM overvoltage. An optimum around 3 V was identified, and this value was chosen as the operating point for SiPM operation.

Using the measured parameter distributions, the feasibility of selecting and grouping tiles with similar characteristics was demonstrated, along with optimization of operating voltages to ensure uniform detector response.

Thus, large-scale SiPM testing for the TAO experiment was successfully completed, confirming the performance of the developed setup and demonstrating its efficiency for the characterization of a large number of photodetectors.

As a result of this work, three papers have been published [17], [18], [19].

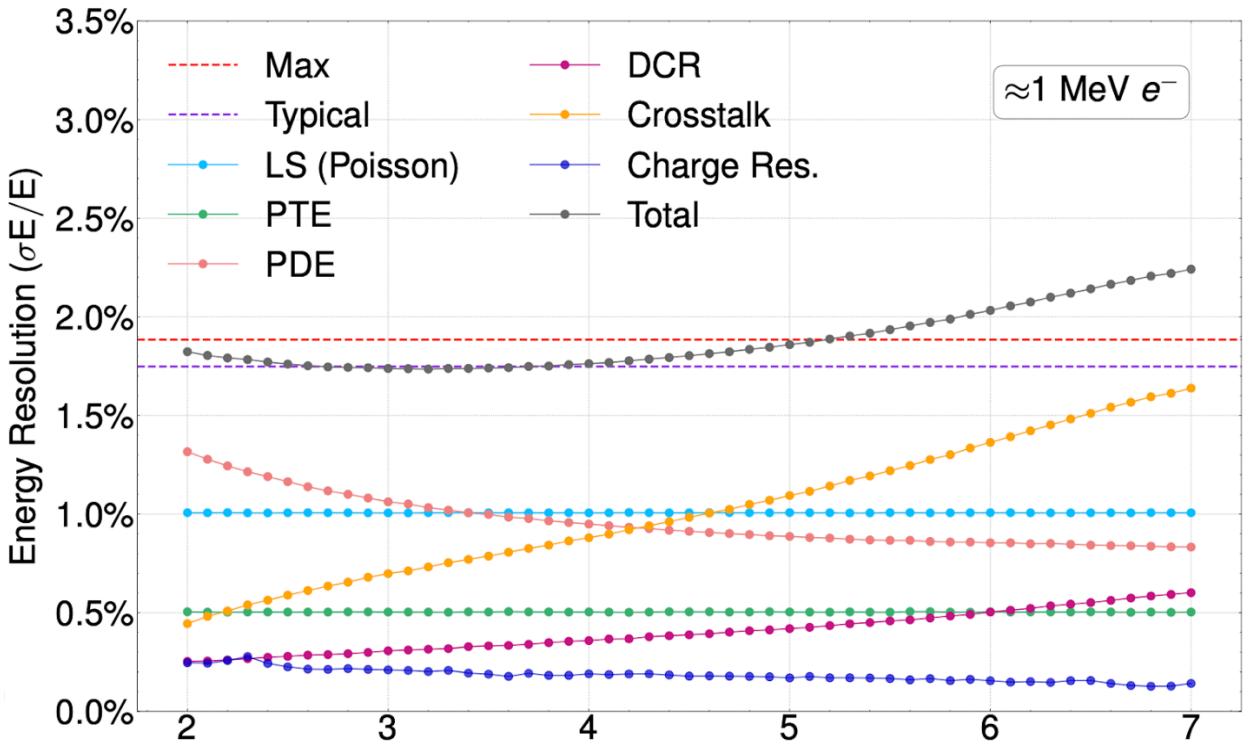


Figure 10. Estimated energy resolution of the TAO detector, including contributions from different components, and its dependence on SiPM overvoltage.

Power system

As part of the development of the JINR-owned SiPM power supply system for the TAO detector, the JINR group, starting from the end of 2023, in collaboration with the company "Marathon," purchased all necessary components for the production of silicon photomultiplier (SiPM) power supplies. In parallel, the manufacturing of key components—motherboards and mezzanine boards equipped with high-voltage DACs—was established at a production site in China.

A total of 40 power supply units were assembled from the manufactured components. For each unit, the control firmware was uploaded, functionality tests were performed, and voltage scale calibration was carried out to compensate for the integral nonlinearity of the DACs. In accordance with the design, all power supplies were compactly installed in two VME crates equipped with a control module based on the PhyCore microcomputer and a CAN-USB interface module, enabling the integration of the crates into a unified CAN network. The temperature dependence of the DACs was also studied [30].

From January to June 2024, comprehensive testing of the reliability and stability of all power supplies under maximum load conditions (200 V, 0.5 mA per channel) was conducted at IHEP

(Beijing). The tests were performed in a configuration corresponding to their final placement in the TAO detector. All units successfully passed the tests. During 2024, a subset of the modules also demonstrated reliable operation as part of the TAO detector prototype, providing power to 100 SiPM tiles. Within these tests, a prototype feedthrough - designed for voltage distribution and for connecting internal and external cables resistant to noise and the aggressive scintillator environment - was successfully validated.

At the beginning of 2025, all power supply units were delivered to the Taishan Nuclear Power Plant site. An initial assembly of the power system was carried out on-site, enabling additional testing of the SiPMs in the “hot” TAO prototype configuration at room temperature. Two feedthroughs were manufactured (Fig. 11, right), providing power to all SiPM matrices and enabling final verification of photodetector signals.

After the completion of the TAO detector assembly and its installation in the operational position relative to the reactor (end of 2025), the power supply system was placed in a temperature-stabilized cabinet and further equipped with power and grounding cables in accordance with the final design (Fig. 11, left). During the uniform routing of internal cables, it was found that a larger number of connectors on the feedthrough was required, which led to the need for three additional power supply modules beyond the initial plan. Considering that some modules were also allocated to the top veto tracker, a decision was made to manufacture an additional 10 modules. For this purpose, assembly and calibration of reserve power supply units were carried out at IHEP (Beijing) from December 2025 to January 2026.

Throughout the project, software for controlling the power supply system was continuously developed and improved. Based on the CANOpen protocol, a software interface providing full functionality for interaction with the hardware was implemented. Communication with the modules is performed via a control unit running a server of this interface. For user convenience, a web client was developed, offering flexible tools for control and monitoring of power supply parameters (see Fig. 12, left).

In addition, at the end of 2025, the power supply system was integrated into the TAO detector control system (DCS) using the developed software interface. This enabled real-time monitoring of the system status, application of voltage calibration corrections, and storage of all parameters in the JUNO-TAO database. The control panel for data synchronization services with the DCS is shown in Fig. 12 (right).

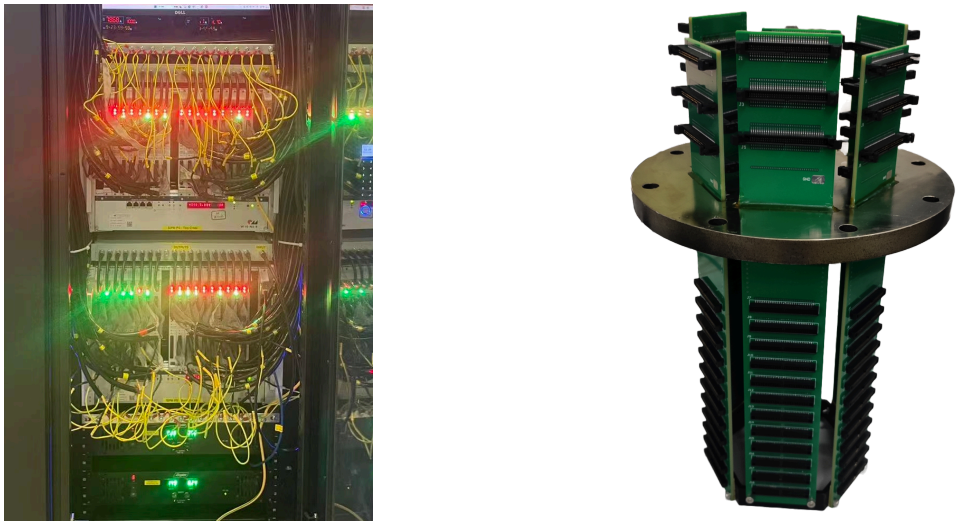


Figure 11. View of the assembled power supply system at the nuclear power plant site in China (left) and the feedthrough (right).

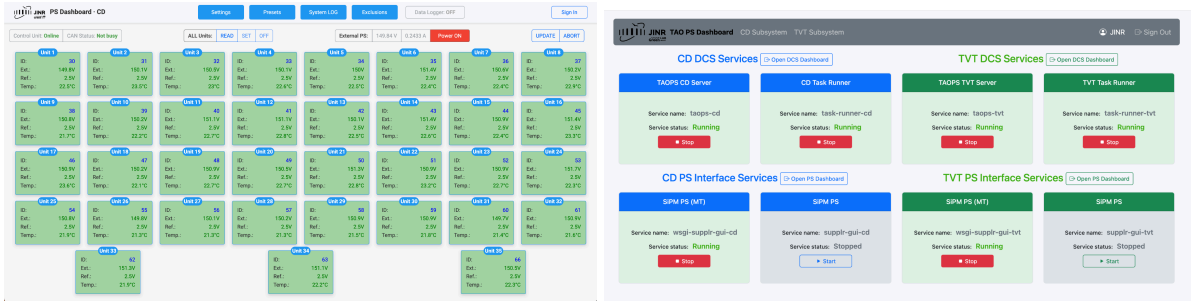


Figure 12. Graphical user interface for controlling the power supply system (left) and the control panel of the data synchronization system between the power supplies and the DCS database (right).

Installation and commissioning

As part of the TAO detector commissioning, the JINR group carried out the following set of activities:

- **November 2024.** In cleanroom conditions, 4024 silicon photomultiplier (SiPM) matrices were installed on two hemispheres of the copper support structure: the matrices were mounted on the inner side, while the front-end electronics were placed on the outer side. For each matrix, a full verification of the signal readout chain was performed, including checks of both low-voltage and high-voltage power lines. This allowed faulty cable lines and individual matrices to be identified and excluded at an early stage.

- **December 2024.** After completing the instrumentation of the structure, the two hemispheres were joined and placed in a light-tight room (see Fig. 13, right). Internal signal, low-voltage, and high-voltage cables were connected.
- **Late December 2024.** The fully assembled copper structure was installed into the cryostat. Feedthrough assemblies for routing power and signal cables were mounted. Test connections of external cables were performed for all channels.
- **March–April 2025.** A repeated comprehensive functionality check of all detector channels was carried out. Identified issues were promptly resolved.
- **October–November 2025.** After relocating the cryostat with the installed copper sphere to its operational position (44 m from the reactor core), final connections of external power and signal cables, including grounding lines, were completed. The power supply and SiPM readout equipment were installed in temperature-stabilized cabinets and configured according to the design specifications (see Fig. 13, left). At this stage, simultaneous powering and comprehensive testing of all detector subsystems were performed, along with network configuration, software debugging, and integration into the detector control system (DCS).

After cooling the detector down to −50 °C and confirming the operability of all channels, test data runs were performed to evaluate the gain of the SiPM matrices for each channel. In addition, channels with elevated noise levels were identified and excluded.

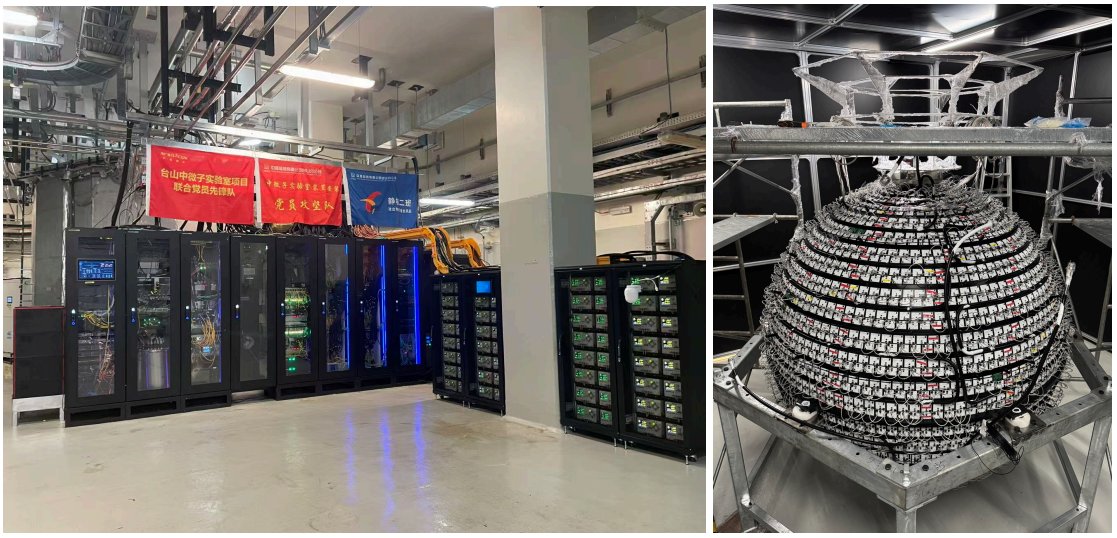


Figure 13. Final view of all electronics used in the TAO detector at the nuclear power plant site in China (left) and the copper shell structure equipped with SiPM matrices on the inner side and electronics on the outer side (right).

Computing and Networking Infrastructure

During the reporting period following the start of data taking, the JINR computing infrastructure, operating within the JUNO Distributed Computing Infrastructure (DCI), has been functioning in line with the initial expectations. At the same time, the actual data rates required adjustments to the data storage solutions.

One of the major changes was the deployment and commissioning of a dedicated storage system based on dCache for the experiment. Previously, a shared storage system of the MICC (EOS), used by multiple projects, was employed. The transition to a dedicated storage system was driven by the increase in data volumes and the need to improve the reliability of the storage system.

At present, about 3.6 PB of effective disk capacity has been deployed in the dCache system, of which approximately 2.8 PB is already in use. Additional disk servers have been procured and will provide about 2.15 PB of additional capacity once commissioned.

No significant changes in computing resources were introduced during the reporting period. The JINR computing center was connected to the EGI accounting system, providing centralized collection and analysis of computing resource usage.

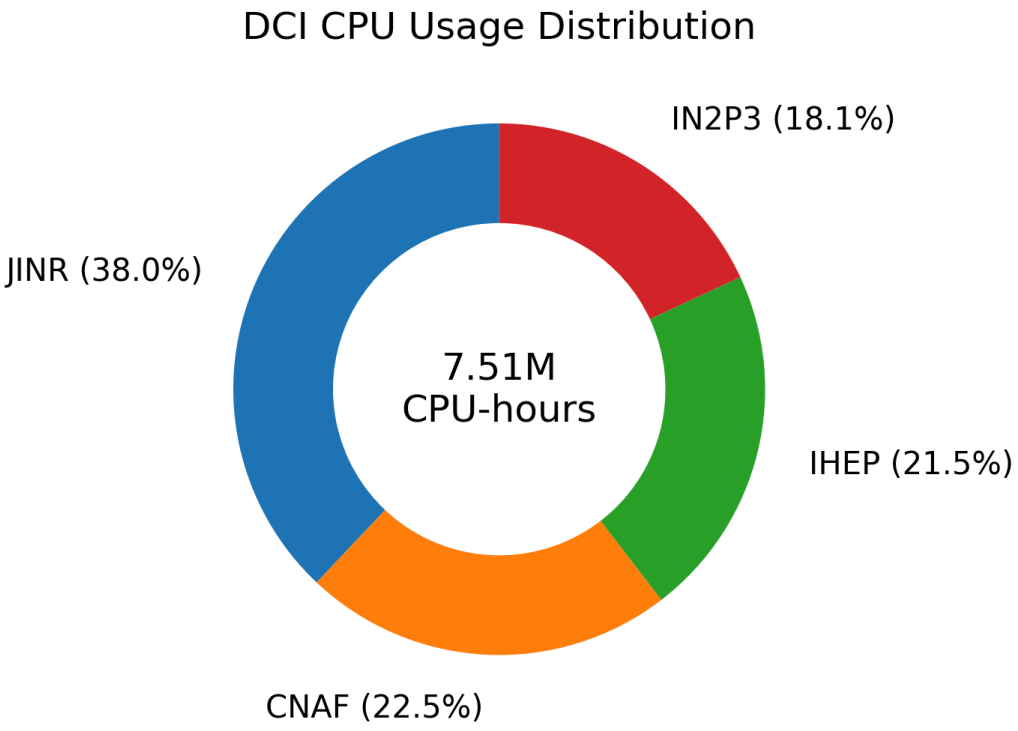


Figure 14. Distribution of computing resource usage within the JUNO DCI from January 2024 to March 2026.

During this period, approximately 38% of the total number of jobs in the JUNO DCI were executed at JINR (see Fig. 14).

Work has also been initiated to restore and further develop the jsub job submission system, originally intended for user analysis and simulation within the JUNO distributed infrastructure. By the start of data taking, support and development of this tool had been discontinued due to limited manpower. Since 2025, development of jsub has been resumed by two PhD students from JINR, including adaptation to the current infrastructure and extension of its functionality. In parallel, the development of user job monitoring tools has been initiated.

To improve network connectivity between JINR and IHEP, an L2VPN connection was established along the route IHEP–CERN–CERNLight–JINR. Previously, communication relied on public networks, which did not provide sufficient or predictable bandwidth.

Data quality of the JUNO experiment

During the reporting period, a monitoring system for Offline Run Validation was developed. The system consists of two main subsystems: Run Validation and Channel Quality. The system is implemented as a web-based application with a graphical user interface for convenient operation.

The Run Validation subsystem visualizes data through interactive plots, allowing users to perform run-level validation and analyze long-term trends over the entire data-taking period. An example of the Run Validation page is shown in Figure 15.

The Channel Quality subsystem tracks the status of detector channels on a per-run basis. It enables the identification of detector instabilities and supports detailed diagnostics at the level of individual channels. In this way, the system maintains a complete history of detector channel behavior throughout the detector's operation.

The system is being developed in close collaboration with the JUNO Data Quality group. Since the start of physics data taking, the group has been working on evaluating detector performance and clarification of criteria for both large and small photomultiplier tubes (PMTs). So far, data collected between August 30, 2025, and the end of February 2026 have been validated. During this period, the characteristics of 17634 large PMTs were analyzed for each dataset (more than 3000 datasets in total). Validation of the small PMTs is still ongoing and has not yet been completed due to technical constraints. The characteristic information is used to produce lists of bad channels, which are excluded from physics analysis. The criteria for channel selection are refined as our understanding of the detector improves. The group also contributes to data selection and validation procedures using the Run Validation subsystem.

The system is actively used for data quality assessment, diagnostics, and identification of potential issues. It also supports the detection of various anomalies, including electronics failures, PMT malfunctions, and issues in raw data processing and transmission, as well as the final selection of high-quality data and reliable detector channels.

Diagnostic plots are generated automatically and made available to shifters, who use them to monitor run conditions and evaluate stability over time. Any irregularities identified during this process are reported to experts for further investigation and decision-making.

The system has been integrated into the data quality workflow, enabling efficient collaboration between shifters and experts and ensuring timely detection of detector performance issues.

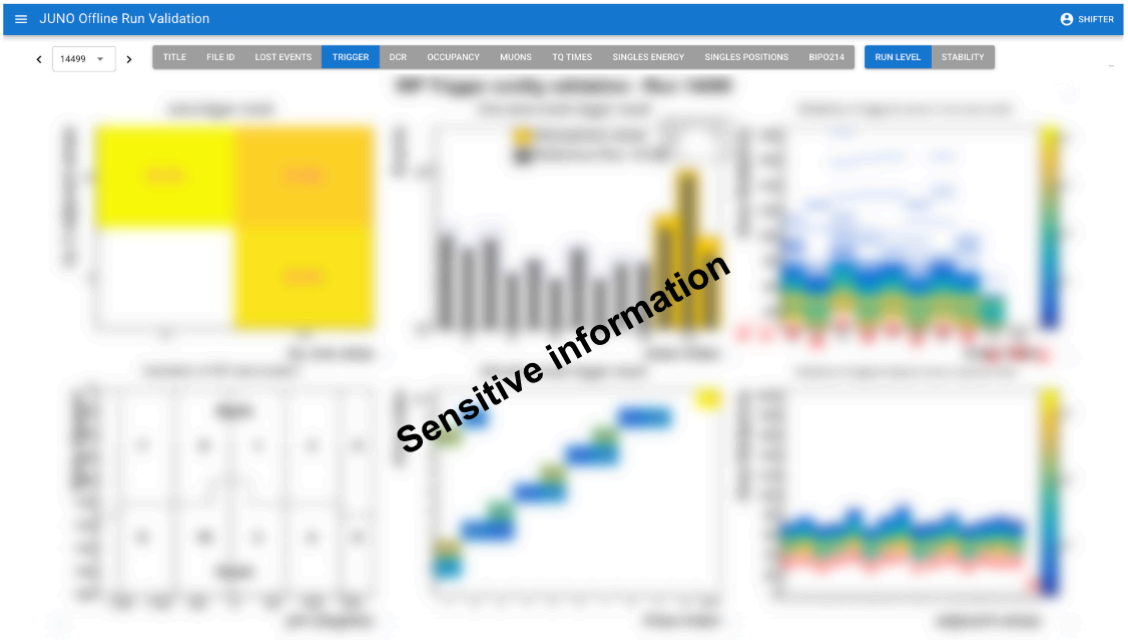


Figure 15. User interface view for analyzing diagnostic graphs. The blur effect is added intentionally since sensitive data is shown.

Intrinsic Scintillator Resolution and Detector Response

We have evaluated the contribution of the intrinsic resolution to the full width of the scintillation line for the JUNO detector using calibration data, following the formalism presented in our group's works [15] and [22].

Definitions

The relative variance of the charge signal for gamma rays is given by ([22]):

(1) $v(Q_\gamma) \equiv \sigma^2(Q_\gamma) / Q_\gamma^2 = (1 + v_1 Det) / Q_\gamma + (Q_1 / Q_\gamma) \cdot v_1^{int} + v_\gamma(Q_\gamma)$,

where:

- $v(Q_\gamma)$ is the relative variance of the total charge signal for a gamma ray with mean energy deposition corresponding to the mean recorded charge Q_γ;
- $v_1 Det$ is the relative variance of the single-electron PMT spectrum averaged over all detector PMTs;
- Q_1 is the mean collected charge for electrons with an energy of 1 MeV (light yield);
- v_1^{int} is a universal parameter describing the contribution of the intrinsic resolution to the total energy resolution for a 1 MeV electron.

In contrast to gamma rays, the response of the liquid scintillator detector to alpha particles contains no contribution from the intrinsic resolution, nor the last term $v_\gamma(Q)$ appearing for gamma radiation only:

(2) $v(Q_a) \equiv \sigma^2(Q_a) / Q_a^2 + v^{Det}(p) = (1 + v_1^{det}) / Q_a + v^{Det}(p)$,

where $v^{Det}(p)$ is the contribution to the total energy resolution related to non-uniformity of light collection (if light-collection compensation depending on source position is absent).

Note. In the first case (for γ-rays), the source is assumed to be point-like, and the term related to detector non-uniformity in light collection is absent. In the case of α-particles, the non-uniformity term may still be present because the source is not point-like; however, for our purposes we can use a quasi-point source located "near the centre", neglecting light-collection non-uniformity. Nevertheless, for generality we keep the term $v^{Det}(p)$.

Parameter estimation from α-particle data (^{214}Po)

The mean response of monoenergetic α-particles from ^{214}Po decay corresponds to an electron energy deposition of 0.93 MeV. The corresponding energy resolution is $(2.8 \pm 0.1)\%$ (the uncertainty was estimated using data from the figure in [2]).

One can write:

(3) $v(Q_a) = (0.028)^2 = (1 + v_1^{Det}) / (0.93 \cdot LY) + v^{Det}(p)$

Hence:

(4) $(1 + v_1^{Det}) / LY = 0.93 \cdot (0.028)^2 - 0.93 \cdot v^{Det}(p) = (7.3 \pm 0.6) \cdot 10^{-4} - 0.93 \cdot v^{Det}(p)$

Parameter estimation from gamma-ray data (511 keV)

The charge response of two 511 keV gamma rays has a visible energy of 0.89 MeV for an electron with a total energy resolution of 3.4 %. The corresponding expression for a single 511 keV gamma ray is as follows:

(5) $v(Q_\gamma) = 2 \cdot v(2 \cdot Q_\gamma) = 2 \cdot (0.034)^2 = (1 + v_1^{Det}) / (0.89 \cdot 0.511 \cdot LY) + (LY) / (0.93 \cdot 0.511 \cdot LY) \cdot v_1^{int} + v_\gamma(Q)$

Substituting $(1 + v_1^{Det})/LY = 7.3 \cdot 10^{-4} - 0.93 \cdot v^{Det}(p)$ from (4), we obtain:

(6) $2 \cdot (0.034)^2 = (23.1 \pm 1.4) \cdot 10^{-4} = [7.3 \cdot 10^{-4} - 0.93 \cdot v^{Det}(p)] / (0.89 \cdot 0.511) + [1 / (0.93 \cdot 0.511)] \cdot v_1^{int} + v_\gamma(Q) = (16.1 \pm 1.2) \cdot 10^{-4} + 2.1 \cdot (v_1^{int} - 0.93 \cdot v^{Det}(p)) + v_\gamma(Q)$

From this we find for v_1^{int}:

(7) $v_1^{int} = [(7.1 \pm 1.8) \cdot 10^{-4} - v_\gamma(Q)] / 2.1 + 0.93 \cdot v^{Det}(p) = (3.4 \pm 0.9) \cdot 10^{-4} - v_\gamma(Q)/2.1 + 0.93 \cdot v^{Det}(p)$

The value of $v_\gamma(Q)$ was estimated by Monte Carlo in [10]; it is at the level of $(1.1\,\%)^2 = 1.3 \cdot 10^{-4}$. As a result we obtain:

(8) $v_1^{int} \approx (2.8 \pm 0.9) \cdot 10^{-4}$

which corresponds to an energy resolution of (1.7 ± 0.25) % for an energy deposition of 1 MeV for electrons.

This result is statistically compatible with previous measurements for liquid organic scintillators from [15] and [22].

Estimation of the light yield LY

Furthermore, one can estimate the value of LY (in photoelectrons per MeV) using equation (2):

(9) $LY = (1 + v_1^{Det}) / [0.93 \cdot v(Q_a)] = (1 + v_1^{Det}) / [0.93 \cdot (7.3 \pm 0.6) \cdot 10^{-4}] = 1473 \cdot (1 + v_1^{Det})$

With $(1 + v_1^{Det}) = 0.48$ we get:

(10) LY = 2180 ± 180 photoelectrons/MeV

If one uses LY ≃1600 photoelectrons/MeV, this leads to an unrealistically small value $v_1^{Det} = 0.09$.

Thus, a simple analysis of the JUNO calibration data leads to the conclusion that the contribution of the intrinsic resolution must be included in the JUNO data analysis.

Data selection and statistical oscillation analysis

In 2025, a detailed sensitivity study of the JUNO experiment to the neutrino mass ordering was published [3], incorporating the most up-to-date design specifications for the JUNO and TAO detectors, as well as the latest background conditions. The study demonstrated that JUNO could achieve a median sensitivity to the mass ordering at the 3σ significance level after 7.1 years of data collection (see fig. 16).

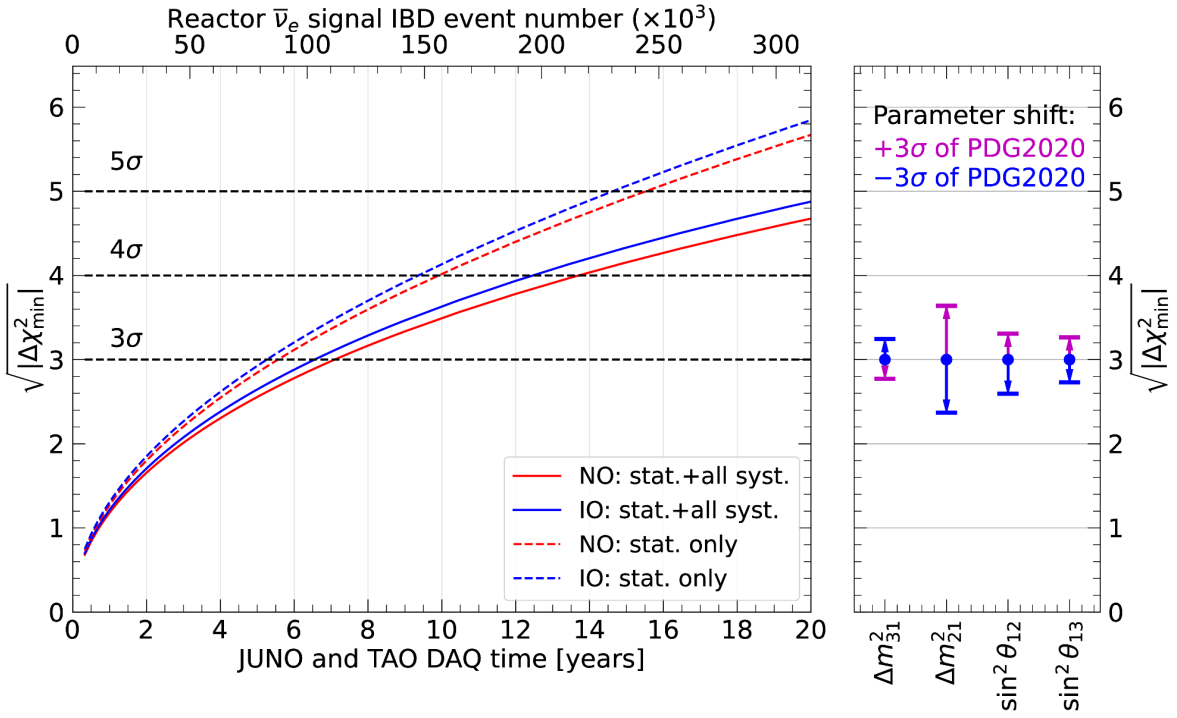


Figure 16. NMO sensitivity ($\Delta\chi^2_{\rm min}$) vs. data-taking time. Left: Results for Normal (NO, red) and Inverted (IO, blue) Mass Ordering. Solid and dashed lines denote full systematic and statistical-only uncertainties, respectively. Assuming an 11/12 reactor duty cycle, JUNO reaches a 3σ (3.1σ) significance after 7.1 years for true NO (IO). Right: Impact of varying the true oscillation parameters on the NO sensitivity at the 7.1 year exposure milestone.

The TAO near detector was commissioned behind schedule, with physics data collection commencing in February 2026. The current objective is to accumulate several months of data to provide the necessary constraints on the shape of the reactor electron antineutrino spectrum, which is essential for measuring oscillation parameters and determining the neutrino mass ordering in JUNO. Consequently, the first TAO-derived constraints on sterile neutrino parameters will be obtained no earlier than the end of 2026.

Between August 26 and November 2, 2025 (a period of 59.1 days), JUNO collected [1] a dataset consisting of 2379 inverse beta decay (IBD) candidates (Fig. 17). Given an estimated background contribution of 34%, the detector registers 47.9 reactor electron antineutrino interactions per day, which is three times lower than the rate expected in the no-oscillation scenario. The oscillation analysis is performed jointly using data from JUNO and the Daya Bay near detectors (see the following section), which provide the necessary constraints on the reactor antineutrino spectral shape. Furthermore, constraints on the oscillation parameters $\sin^2\theta_{13}$ and Δm^2_{31} obtained from Daya Bay were also incorporated into the analysis. As a result, the most precise measurements to date of two neutrino oscillation parameters were obtained (Fig. 18-20):

- $\sin^2\theta_{12} = 0.3092 \pm 0.0087$,
- $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}$ eV^2.

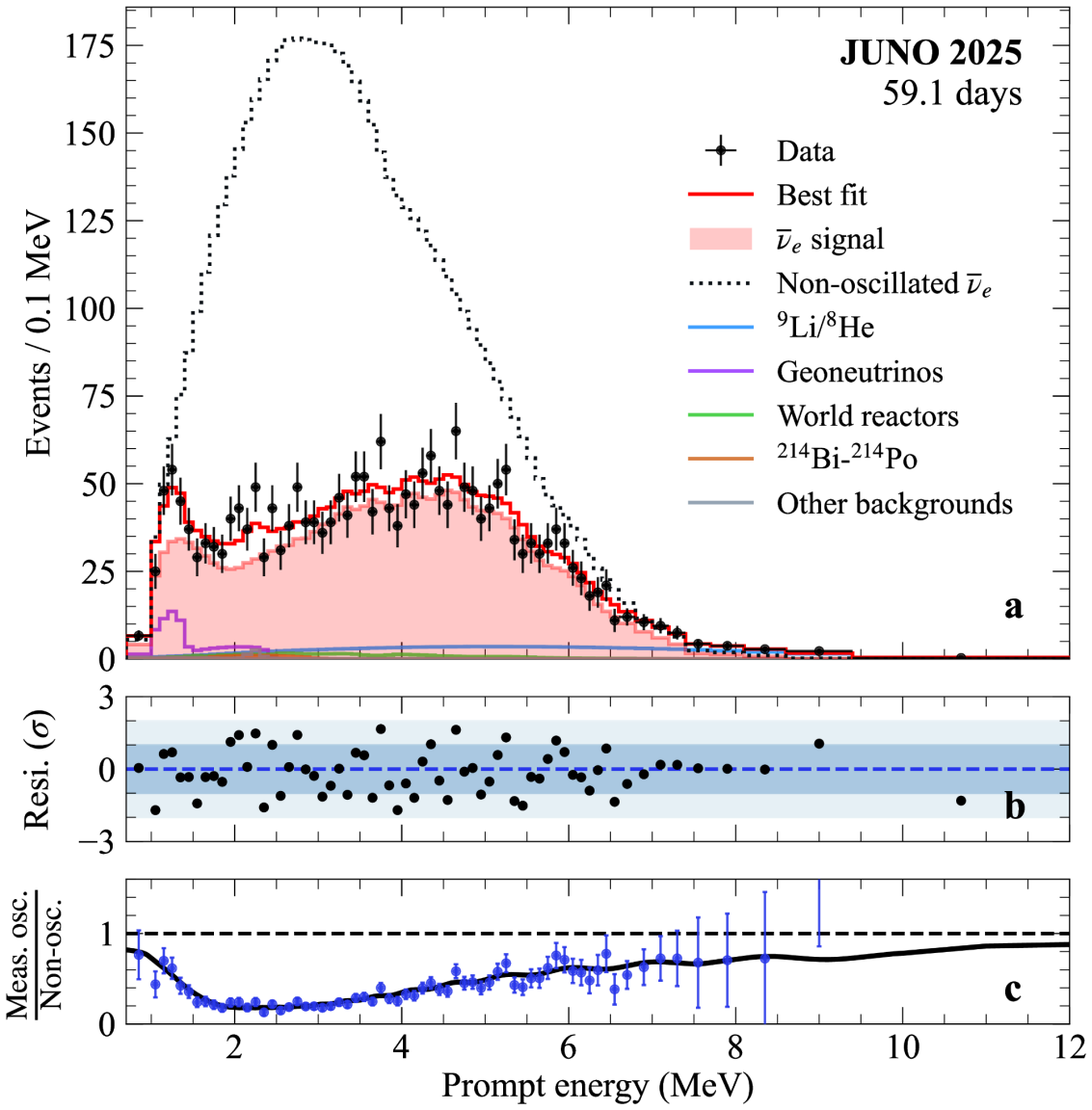


Fig. 17. Measured prompt energy spectrum of IBD candidates. a) Data (black points) compared to the best-fit oscillation model (red curve). The shaded red area represents the expected antineutrino signal. The solid black line and its shaded band show the non-oscillated expectation and its systematic uncertainty, respectively. Backgrounds are denoted by solid colored lines. b) Residuals illustrating the data-model consistency. c) Ratio of the measured spectrum to the non-oscillated prediction.

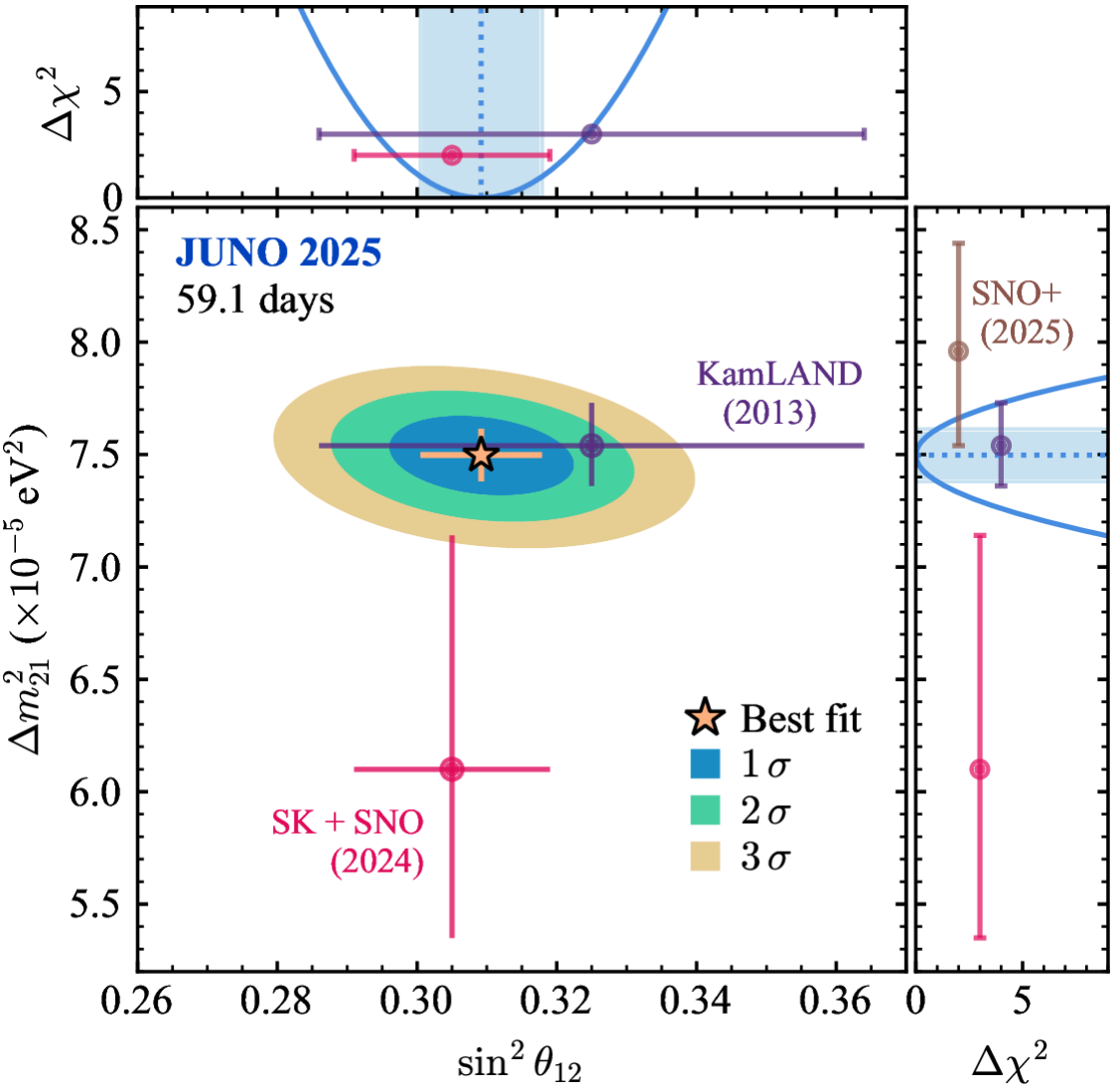


Fig. 18. Results on solar oscillation parameters. Confidence regions (1σ, 2σ, and 3σ) for $\sin^2\theta_{12}$ and Δm^2_{21} derived from the prompt energy spectrum fit. The upper and right panels show the 1D χ^2 profiles for $\sin^2\theta_{12}$ and Δm^2_{21}, respectively, along with their 1σ intervals. The star indicates the JUNO best-fit point.

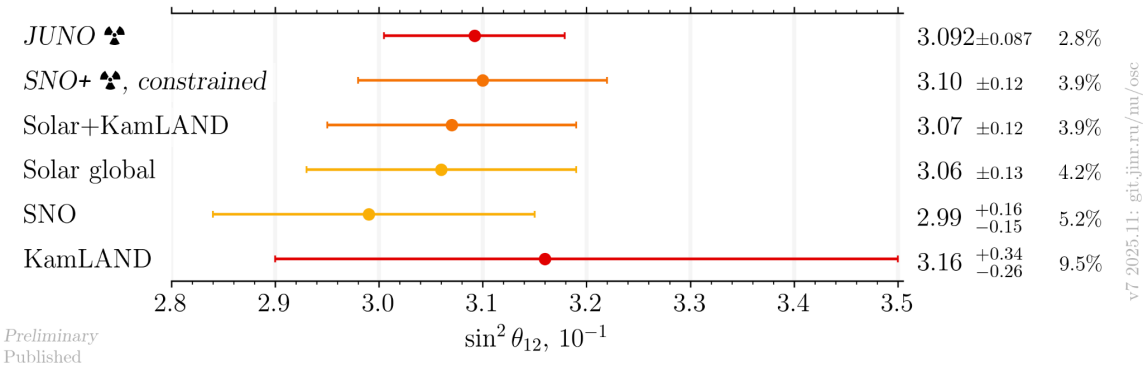


Fig. 19. Comparison of $\sin^2\theta_{12}$ measurements in JUNO with other global oscillation experiments.

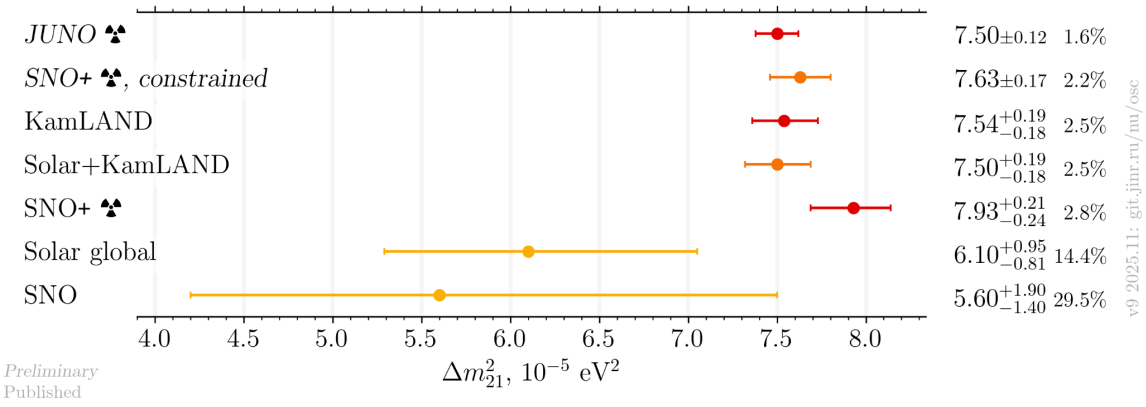


Fig. 20. Comparison of Δm^2_{21} measurements in JUNO with other global oscillation experiments.

Both the sensitivity studies and the data analysis results were obtained with the direct participation of scientists from the DLNP JINR. Within the reactor neutrino analysis group, three independent research teams are active. The Dubna team works on the analysis in collaboration with colleagues from Shanghai Jiao Tong, Shandong, and Tsinghua Universities, among others. The responsibilities of the Dubna scientists include the following tasks: performing the joint statistical oscillation analysis of the JUNO, Daya Bay, and soon, TAO detectors; IBD event selection in JUNO and estimation of the detection efficiency; evaluating the spectral shape and the contribution of background events (accidental coincidences, ^{9}Li/^{8}He, fast and double neutrons, and the α-n reaction); and muon track reconstruction. Furthermore, staff members participate in core collaboration activities, including data-taking shifts at the JUNO detector, data quality (DQ) control, and data production shifts.

The oscillation analysis performed by our group is implemented directly within the GNA framework, which is developed and maintained by the DLNP JINR team.

Open release of the Daya Bay data and constraining the shape of the reactor antineutrino spectrum

Over ten years of operation, the Daya Bay experiment accumulated a record-breaking dataset of reactor electron antineutrino interactions and yielded the most precise measurement of the neutrino mixing parameter $\sin^2 2\theta_{13}$. In December 2025, the complete Daya Bay data archive, comprising 5.55 million events, was made publicly available via the Zenodo repository (https://zenodo.org/records/17587229).

Particular emphasis has been placed on the reproducibility of results. To this end, the dayabay-model-official software package (https://pypi.org/project/dayabay-model/) was developed and released. It reproduces the antineutrino spectrum prediction procedure and enables oscillation analysis using the open data. The software supports all four open data formats. Additionally, a lightweight version of the dataset has been hosted on the Python Package Index (https://pypi.org/project/dayabay-data-official/), making all necessary code and data for the analysis accessible to users via a single installation command.

The preparation of this data and software was carried out by JINR staff over a period of three years.

Despite being associated with the now-completed Daya Bay project, this development is of big importance for the JUNO data analysis due to the temporary absence of data from the TAO near detector. The developed model and the open data from the Daya Bay near detectors have been utilized

by research groups from JINR and Shanghai to constrain the reactor electron antineutrino spectrum. The analysis was implemented as a simultaneous fit of the combined χ^2 from JUNO and the Daya Bay near-detector data, where the Daya Bay χ^2 for each set of minimization parameters was calculated using the dayabay-model-official software.

It should be noted that, ideally, the reactor antineutrino spectrum should be constrained by a detector with an energy resolution comparable to or better than that of JUNO (3.4%). The Daya Bay detectors have a resolution of σ=8.6% at 1 MeV, which can not fully constrain all degrees of freedom available to JUNO, nor does it permit a completely model-independent measurement of Δm^2_{31}. However, when an external constraint is applied to Δm^2_{31}, Daya Bay's precision is sufficient for measuring the "solar" oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$. Monte Carlo simulations have demonstrated that even extreme fluctuations in the antineutrino spectral shape, whether resulting from variations in the decay branch contributions of uranium and plutonium fission isotopes or from synthetic distortions, do not lead to a bias in the measured solar oscillation parameters.

Development of dag-modelling — new framework for statistical analysis

Specifically for the Daya Bay open data release, a new framework for statistical analysis, dag-modelling[28], was developed (https://pypi.org/project/dag-modelling). The framework builds upon the concepts established in its predecessor, GNA, and enables the construction of analysis models as directed acyclic graphs (DAGs). In this architecture, nodes operate on data arrays and are computed using lazy evaluation (on-demand). The framework is implemented in Python and is accessible via the standard package manager (pip). By utilizing Just-In-Time (JIT) compilation, array-based operations, and lazy evaluation, the inherent overhead of Python is significantly reduced. The open model of the Daya Bay experiment and its corresponding analysis implemented in dag-modelling (https://git.jinr.ru/dagflow-team/dayabay-analysis) have demonstrated the high efficiency of this approach, with the framework's own overhead maintained at approximately 25%.

Porting the JUNO experiment model from GNA to dag-modelling (https://git.jinr.ru/dagflow-team/dgm-juno-dev) is currently 90% complete. Adopting dag-modelling for future analyses will provide:

- Standardized Tools: The use of common, rigorously tested tools for statistical neutrino oscillation analysis (JUNO+TAO, Daya Bay, etc.) and for conducting joint measurements.
- Streamlined Delivery: Simplified distribution of data and tools to both collaboration members and external users.
- Open Science: The ability to create open-access models, following the precedent set by Daya Bay.
- Educational Resources: Facilitating the development of training and educational materials.

Furthermore, the ongoing optimization and development of the framework will enhance computational performance across all models. Future milestones include GPU support, automatic differentiation (to accelerate derivative calculations for minimization), and more efficient implementations of core operations.

Sensitivity to atmospheric neutrino oscillations

Although JUNO is a liquid scintillator detector, it nonetheless possesses directional sensitivity to high-energy muons and electrons, achieving an angular resolution of approximately 10° for energies above 2.5 GeV. This capability enables the selection of the upward-going flux of high-energy particles,

[28] During the initial stages of development and in the previous renewal proposal, the project was referred to as dagflow.

specifically, those associated with muon and electron neutrinos passing through the Earth. The presence of the Earth's matter effect distinctively distorts the oscillation probabilities for neutrinos with energies around 5 GeV that traverse the Earth's core ($\cos\theta<-0.8$). This distortion is most pronounced for muon and electron neutrinos under the Normal Mass Ordering (NO) hypothesis, and for muon and electron antineutrinos under the Inverted Mass Ordering (IO) hypothesis. Consequently, JUNO has the capability to determine the neutrino mass ordering utilizing atmospheric neutrinos.

The JINR group has implemented a model within the GNA framework that predicts the expected two-dimensional distribution of atmospheric neutrino events as a function of energy and direction. The model incorporates two flavors (e, μ), two particle types (neutrinos and antineutrinos), direction-dependent Earth matter interactions, two interaction channels (Charged Current and Neutral Current), energy smearing, energy-dependent angular smearing, particle misidentification during reconstruction, as well as systematic uncertainties (including cross-sections, atmospheric flux and spectrum, and particle identification efficiency).

The sensitivity to the neutrino mass ordering using atmospheric neutrinos was evaluated[29], along with the expected uncertainties for the oscillation parameters. It was demonstrated that after 10 years of data taking, JUNO will achieve a significance of 2.1σ (1.4σ) for the Normal (Inverted) mass ordering (see fig. 21). Furthermore, JUNO will attain a precision of 2% and 1.8% for the oscillation parameters Δm^2_{21} and $\sin^2\theta_{23}$, respectively, based on atmospheric neutrino interactions.

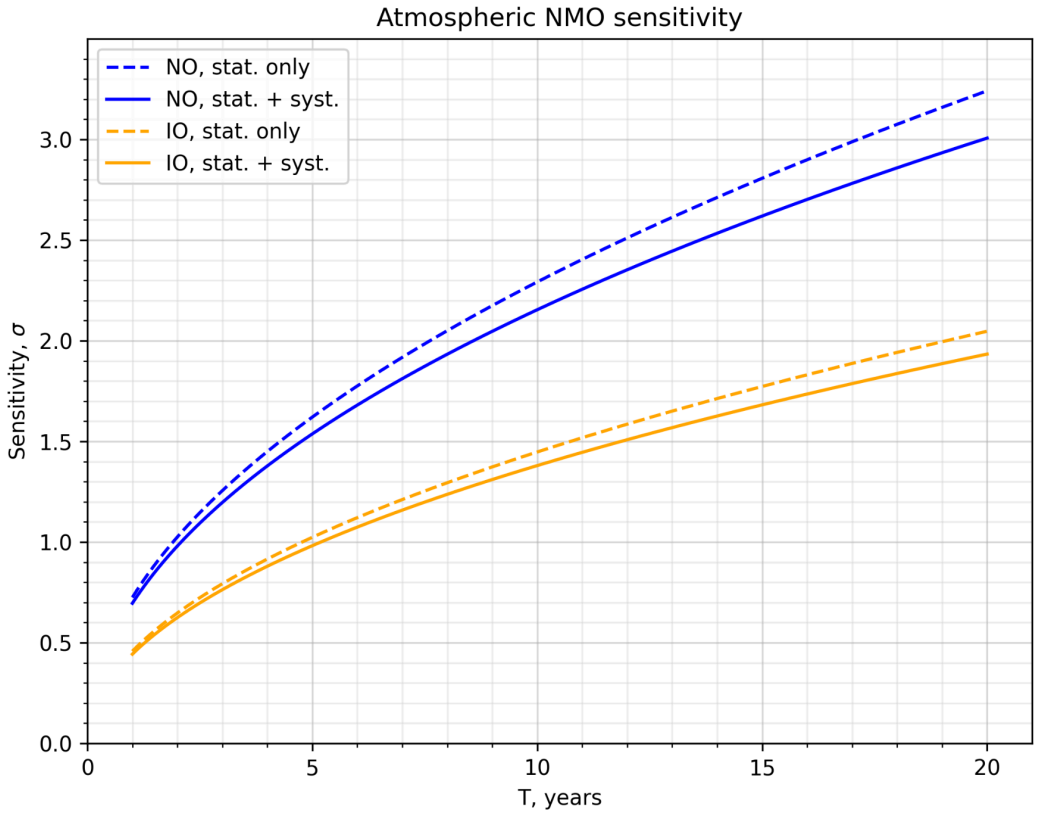


Figure 21. JUNO Sensitivity to the Neutrino Mass Ordering Using Atmospheric Neutrinos.

[29] Nikita Bessonov, Master's thesis, *"Evaluation of the JUNO sensitivity to neutrino oscillation parameters using atmospheric neutrinos"*, Lomonosov Moscow State University (MSU), 2024.

2.2.4. A list of the main publications of JINR authors, including associated personnel on the results of the project work (list of bibliographical references).

[1] JUNO collaboration. “First measurement of reactor neutrino oscillations at JUNO”. In: (Nov. 2025). arXiv: 2511.14593 [hep-ex].

[2] JUNO collaboration. “Initial performance results of the JUNO detector”. In: (Nov. 2025). arXiv: 2511.14590 [hep-ex].

[3] JUNO collaboration. “Potential to identify neutrino mass ordering with reactor antineutrinos at JUNO”. In: Chin. Phys. C 49.3 (2025), p. 033104. doi: 10.1088/1674-1137/ad7f3e. arXiv: 2405.18008 [hep-ex].

[4] JUNO collaboration. “The JUNO experiment Top Tracker”. In: Nucl. Instrum. Meth. A 1057 (2023), p. 168680. doi: 10.1016/j.nima.2023. 168680. arXiv: 2303.05172 [hep-ex].

[5] JUNO collaboration. “Sub-percent precision measurement of neutrino oscillation parameters with JUNO”. In: Chin. Phys. C 46.12 (2022), p. 123001. doi: 10.1088/1674-1137/ac8bc9. arXiv: 2204.13249 [hep-ex].

[6] Daya Bay collaboration. “Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay”. In: Phys. Rev. Lett. 130.16 (2023), p. 161802. doi: 10.1103/PhysRevLett.130.161802. arXiv: 2211.14988 [hep-ex].

[7] JUNO collaboration. “JUNO physics and detector”. In: Prog. Part. Nucl. Phys. 123 (2022), p. 103927. doi: 10.1016/j.ppnp.2021.103927. arXiv: 2104.02565 [hep-ex].

[8] A. Gavrikov, D. Dolzhikov, M. Gonchar et al. “Simulation-based inference for precision neutrino physics through neural Monte Carlo tuning”. In: Commun. Phys. 9.1 (2026), p. 63. doi: 10.1038/s42005-026-02499-6. arXiv: 2507.23297 [physics.data-an].

[9] Y. Ren, N. Anfimov et al. “Development of a comprehensive PMT optical model for the JUNO experiment”. In: (Jan. 2026). arXiv: 2601.19081 [hep-ex].

[10] JUNO collaboration. “Prediction of Energy Resolution in the JUNO Experiment”. In: Chin. Phys. C 49.1 (2025), p. 013003. doi: 10.1088/ 1674-1137/ad83aa. arXiv: 2405.17860 [hep-ex].

[11] JUNO collaboration. “Simulation of the background from 13C(α, n)16O reaction in the JUNO scintillator”. In: Eur. Phys. J. C 85.9 (2025), p. 1080. doi: 10.1140/epjc/s10052-025-14333-4. arXiv: 2503.00968 [physics.ins-det].

[12] D. Dolzhikov. “JUNO’s Sensitivity to Neutrino Mass Ordering (on behalf of the JUNO Collaboration)”. In: Phys. Part. Nucl. Lett. 22.5 (2025), pp. 1125–1128. doi: 10.1134/S1547477125701274.

[13] Min Li, N. Anfimov, D. Korablev, A. Olshevskiy et al. “Dark count rate stability of JUNO 20-inch PMTs in mass testing”. In: JINST 20.09 (2025), P09007. doi: 10.1088/1748-0221/20/09/P09007. arXiv: 2506.15164 [physics.ins-det].

[14] Caimei Liu, N. Anfimov, D. Korablev, A. Olshevskiy et al. “JUNO 20-inch PMT and electronics system characterization using large pulses of PMT dark counts at the Pan-Asia testing platform”. In: JINST 20.12 (2025), P12013. doi: 10.1088/1748-0221/20/12/P12013. arXiv: 2506.21179 [physics.ins-det].

[15] O. Smirnov. “Intrinsic energy resolution of organic scintillators”. In: Eur. Phys. J. Plus 140.11 (2025), p. 1114. doi: 10.1140/epjp/s13360-025-07055-9. arXiv: 2506.03208 [physics.ins-det].

[16] JUNO collaboration. “The design and technology development of the JUNO central detector”. In: Eur. Phys. J. Plus 139.12 (2024), p. 1128. doi: 10.1140/epjp/s13360-024-05830-8. arXiv: 2311.17314 [physics.ins-det].

[17] X. Chen, N. Anfimov, A. Rybnikov et al. “Burn-in test and thermal performance evaluation of Silicon Photomultipliers for the JUNO-TAO experiment”. In: JINST 19.07 (2024), P07028. doi: 10.1088/1748-0221/19/07/P07028. arXiv: 2406.12912 [physics.ins-det].

[18] Y. Guan, N. Anfimov, D. Fedoseev, K. Kuznetsova, A. Rybnikov, A. Selyuinin, A. Sotnikov et al. “Study of Silicon Photomultiplier external cross-talk”. In: JINST 19.06 (2024), P06024. doi: 10.1088/1748-0221/19/06/P06024. arXiv: 2312.12901 [physics.ins-det].
[19] A. Rybnikov et al. “Performance of the mass testing setup for arrays of silicon photomultipliers in the TAO experiment.” In: JINST 19.05 (2024), P05035. doi: 10.1088/1748-0221/19/05/P05035. arXiv: 2402.05487 [physics.ins-det].
[20] L.D. Kolupaeva, M.O. Gonchar, A.G. Olshevskiy, O.B. Samoylov, “Neutrino oscillations: status and prospects for the determination of neutrino mass ordering and the leptonic CP-violation phase”. In: Phys. Usp. vol.8 (2023), pp. 753–774. doi: 10.3367/UFNr. 2022.05.039191.
[21] Caimei Liu, N. Anfimov, D. Korablev, A. Olshevskiy et al. “Check on the features of potted 20-inch PMTs with 1F3 electronics prototype at Pan-Asia”. In: JINST 18.02 (2023), P02003. doi: 10.1088/1748-0221/18/02/P02003. arXiv: 2208.08264 [physics.ins-det].
[22] O. Smirnov. “Note on intrinsic resolution in liquid organic scintillators”. In: JINST 18.10 (2023), P10026. doi: 10.1088/1748-0221/18/10/P10026. arXiv: 2309.09806 [physics.ins-det].
[23] O. Smirnov et al. “Magnetic shielding for large photoelectron multipliers for the OSIRIS facility of the JUNO detector”. In: JINST 18.04 (2023), P04015. doi: 10.1088/1748-0221/18/04/P04015. arXiv: 2212.02562 [physics.ins-det].
[24] Rong Zhao, N. Anfimov, D. Korablev, A. Olshevskiy, A. Rybnikov et al. “Afterpulse measurement of JUNO 20-inch PMTs”. In: Nucl. Sci. Tech. 34.1 (2023), p. 12. doi: 10.1007/s41365-022-01162-3. arXiv: 2207.04995 [physics.ins-det].
[25] JUNO collaboration. “Mass testing and characterization of 20-inch PMTs for JUNO”. In: Eur. Phys. J. C 82.12 (2022), p. 1168. doi: 10.1140/epjc/ s10052-022-11002-8. arXiv: 2205.08629 [physics.ins-det].
[26] Lukas Bieger, M. Gromov, O. Smirnov et al. “Potential for a precision measurement of solar pp neutrinos in the Serappis experiment”. In: Eur. Phys. J. C 82.9 (2022), p. 779. doi: 10.1140/epjc/s10052-022-10725-y. arXiv: 2109.10782 [physics.ins-det].
[27] N. Anfimov et al. “Study of Silicon Photomultiplier Performance at Different Temperatures”. In: Nucl. Instrum. Meth. A 997 (2021), p. 165162. doi: 10.1016/j.nima.2021.165162. arXiv: 2005.10665 [physics.ins-det].
[28] Zhen Qian, A. Gavrikov, M. Gonchar, Yu. Malyshkin, K. Treskov et al. “Vertex and energy reconstruction in JUNO with machine learning methods”. In: Nucl. Instrum. Meth. A 1010 (2021), p. 165527. doi: 10.1016/j.nima.2021.165527. arXiv: 2101.04839 [physics.ins-det].
[29] Björn Wonsak, N. Anfimov, A. Olshevskiy et al. “A container-based facility for testing 20’000 20-inch PMTs for JUNO”. In: JINST 16.08 (2021), T08001. doi: 10.1088/1748-0221/16/08/T08001. arXiv: 2103.10193 [physics.ins-det].
[30] Selyunin, A.S., Anfimov, N.V., Rybnikov, A.V. *et al.* Study of the Temperature Stability of the High-Voltage DAC AD5535 for Powering Silicon Photomultipiers. *Phys. Part. Nuclei Lett.* 20, 1419–1424 (2023). https://doi.org/10.1134/S154747712306033X

4. Plan/actual analysis of resources used: human (including associated personnel), financial, IT, infrastructure

4.1. Human resources (actual at the time of reporting, total number of participants)
(total number of participants)

№№ п/а	Category employee	Core staff Amount of FTE	Associated personnel Amount of FTE
1.	scientific staff	10.9	0
2.	engineers	7.1	0
3.	professionals	—	—
	Total:	**18**	**0**

Theme Leader

_____/_____/
"_____"_____ 2026

Project Leader

_____/_____/
"_____"_____ 2026

Laboratory Economist

_____/_____/
"_____"_____ 2026