Status and prospects of the JUNO experiment

🟢 **Matthias Raphael Stock, on behalf of the JUNO collaboration**

Technical University of Munich, TUM School of Natural Sciences, Department of Physics,
James-Franck-Str. 1, 85748 Garching, Germany

raphael.stock@tum.de

*The 17th International Workshop on
Tau Lepton Physics (TAU2023)
Louisville, USA, 4-8 December 2023*

Abstract

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment currently under construction in China. It is located 52.5 km away from two nuclear power plants in a newly constructed 700-m-deep underground laboratory. JUNO will be the largest liquid scintillator (LS) detector in the world comprising 20 kt of ultra-pure LS filled in an acrylic sphere. Its main goal is to determine the neutrino mass ordering by measuring the energy spectrum of reactor neutrinos with highest accuracy. In addition, JUNO will cover precision measurements of oscillation parameters and several aspects in the field of astroparticle physics. Data taking will start in late 2024.

1 Introduction

One of the most important current missions in neutrino physics is to determine the neutrino mass ordering (NMO). Since neutrino oscillations are enhanced by the matter effect, the positive mass splitting of $\Delta m_{21}^2 = m_2^2 - m_1^2 > 0$ is observed by solar neutrino experiments. The question remains whether the third mass eigenstate m_3 is the heaviest or the lightest leading to two possible scenarios of normal ordering (NO) and inverted ordering (IO), respectively. The primary goal of the Jiangmen Underground Neutrino Observatory (JUNO) is to determine the NMO by studying the oscillation pattern of reactor neutrinos. JUNO is currently under construction in the Guangdong province in South China. It is located in a newly constructed 700-m-deep underground laboratory (1,800 m.w.e.) at an average distance of 52.5 km to eight reactor cores of the two nearest nuclear power plants Yangjiang and Taishan, which have a combined thermal power of 26.6 GW$_{\text{th}}$ [1]. The medium-baseline is chosen because the survival probability of electron antineutrinos $\overline{\nu}_e$ emitted from the reactor cores is minimal as Figure 1 (Left) illustrates. Here, the 'slow solar oscillation' pattern causes the global minimum and depends on Δm_{21}^2 and $\sin^2 2\theta_{12}$ while the 'fast atmospheric oscillation' pattern

causes the superimposed ripples and depends on Δm_{31}^2 and $\sin^2 2\theta_{13}$. Therefore, this optimal location enables the first-time precision measurement of two oscillation patterns in one energy spectrum. Compaired to long-baseline experiments, the advantage of reactor experiments is that the survival probability is vacuum-dominated and independent of the mixing angle θ_{23} and the CP-violating phase δ_{CP}. Figure 1 (Right) illustrates the expected energy spectra after six years of data taking. Absolute value and sign of Δm_{31}^2 lead to the different position of the ripples in the energy spectra of NO and IO. JUNO can distinguish between the two scenarios and reveal the realized NMO in Nature by recording large statistics and in high precision.
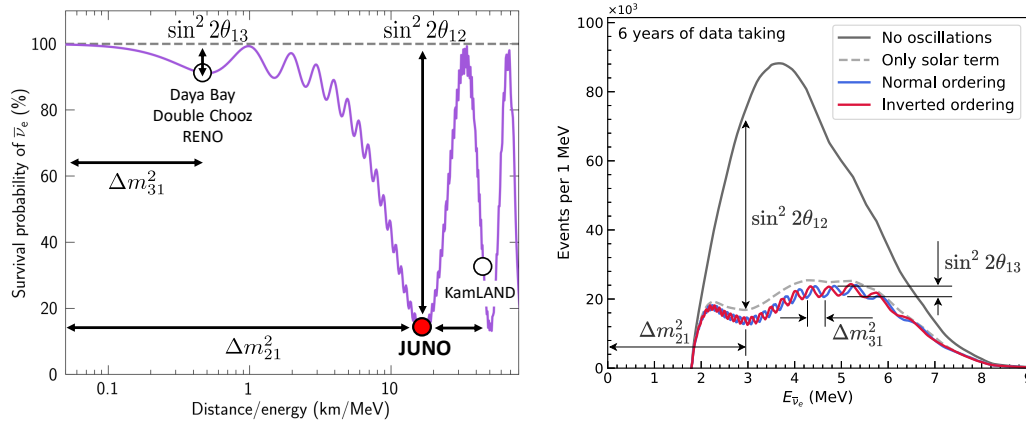
Figure 1: **Left:** JUNO is located where the survival probability of the reactor neutrinos is minimal. **Right:** Expected reactor neutrino energy spectra are illustrated assuming perfect detector resolution of JUNO and six years of data taking [1].

2 Detector design and status

The ability to resolve the NMO sets demanding design requirements for the detector. Civil construction of the JUNO site was completed in December 2021. JUNO will be the largest liquid scintillator (LS) detector in the world comprising 20 kt of ultra-pure LS filled in a 35.4-m-diameter acrylic sphere. The vast volume is monitored by 17,612 large 20-inch and 25,600 small 3-inch photomultiplier tubes, denoted as LPMT and SPMT, respectively. They are mounted on a stainless steel support structure that was finished in June 2022 followed by the assembly of acrylic panels forming the sphere. Figure 2 presents an overview of the JUNO detector. The central detector (CD) ensures a photocathode coverage of 78 % and provides an unprecedented energy resolution of better than 3 % at 1 MeV. The CD is surrounded by the 43.5-m-diameter cylindrical water Cherenkov detector (WCD) comprising 35 kt of ultra-pure water viewed by 2,400 LPMTs. The WCD provides a veto for cosmic muons and shields the CD from environmental radioactivity [1–3]. The Top Tracker (TT) covers 60 % of the CD and WCD and measures 30 % of cosmic muons passing through the CD with a median resolution of 0.2 % at the bottom of the WCD. Combined with the CD and WCD, the TT provides well reconstructed muon samples with > 99 % purity to calibrate and tune reconstruction algorithms and veto affected regions [3, 4]. Several subsystems use radioactive sources or pulsed UV light to regulary calibrate the energy scale, which is necessary due to the non-linearity of the LS [5]. The precision of the absolute energy scale better than 1 % is guaranteed [1–3].
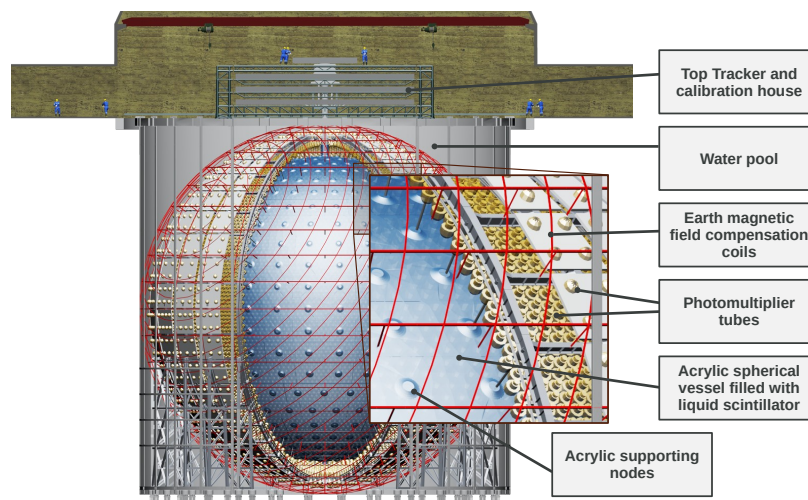
Figure 2: Overview of the JUNO detector [1].
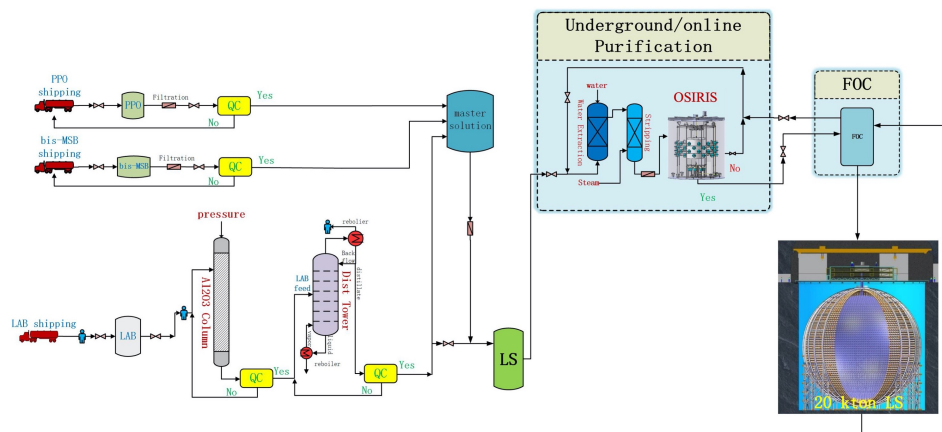
Figure 3: Overview of the liquid scintillator systems with purification chains above ground and underground including the pre-detector OSIRIS [3].

2.1 Liquid scintillator purification and OSIRIS

The liquid scintillator (LS) of JUNO is composed of LAB (linear alkylbenzene) as the solvent mixed with 2.5 g/L PPO (2,5-diphenyloxazole) as fluor and 3 mg/L bis-MSB (1,4-bis(2-methylstyryl)benzene) as additional wavelength shifter [6]. Optical properties are crucial and require, e.g., very high light yield of about 10,000 photons per MeV and an attenuation length $\gtrsim 20$ m at 430 nm due to the size of the CD. Radiopurity is crucial requiring U/Th concentrations of $\lesssim 10^{-15}$ g/g for the NMO determination and $\lesssim 10^{-17}$ g/g for solar neutrino measurements. Therefore, the LS passes a chain of purification steps onsite as Figure 3 shows. Before the LS mixing, the LAB goes through the Al_2O_3 column to remove optical impurities. The distillation plant removes heavy and high-boiling radioactive materials such as ^{238}U, ^{232}Th and ^{40}K. Then, the LS will be mixed with PPO and bis-MSB, pumped underground where water extraction and steam stripping are applied to purify further and remove gaseous impurities, respectively [7]. The quality of a fraction of the produced LS is checked by the Online Scintillator Internal Radioactivity Investigation System (OSIRIS) before and during the filling of the CD. OSIRIS acts as a pre-detector and verifies the radiopurity and optical properties of the LS [8]. The purification plants and OSIRIS are currently under commissioning.

2.2 Taishan Antineutrino Observatory

The Taishan Antineutrino Observatory (TAO) [9] is a satellite detector of JUNO located 44 m away from the Taishan reactor core 1. Its purpose is to measure the unoscillated antineutrino energy spectrum with extremely high statistics and in unprecedented high-resolution, which is smaller than 2 % at 1 MeV. This model-independent reference spectrum reduces the shape uncertainty and improves the sensitivity of JUNO for the NMO. Besides, TAO provides benchmark measurements to test nuclear databases. It also allows to search for short neutrino oscillations caused by hypothetical coupling of sterile neutrinos to the flavor eigenstates violating the unitarity of the usual 3 × 3 mixing matrix. TAO uses novel detector technologies, e.g., 10 m^2 of silicon photomultipliers with 50 % detection efficiency achieve an almost full optical coverage of the 2.8 t gadolinium-loaded LS volume operated at −50°C [9]. The TAO detector has been assembled and tested at the IHEP and will be moved to the Taishan site in 2024.

3 Physics prospects

JUNO will have a broad and rich physics program due to its large detector target mass, excellent energy resolution, outstanding radiopurity and good shielding. Beyond the determination of the NMO, JUNO will measure several neutrino mixing parameters with sub-percent precision, significantly contribute to the field of astroparticle physics and search for physics beyond the Standard Model of Particle Physics [2,3]. A few examples are highlighted in the following.

3.1 Neutrino mass ordering and neutrino oscillation parameters

JUNO measures approximately 45 reactor neutrino events per day via the inverse beta decay (IBD), $\overline{\nu}_e + p \rightarrow e^+ + n$, which has an energy threshold of $E_{thr} = 1.8$ MeV and features a time-correlated scintillation signature in the detector. The prompt signal is caused by the scintillation of the positron e^+ and its annihilation producing two gammas of $E_\gamma = 0.511$ MeV each exciting the LS. The antineutrino energy $E_{\overline{\nu}_e}$ can be reconstructed from the energy deposition of the positron, i.e., $E_{prompt} = 2 \times E_\gamma + E_{\overline{\nu}_e} - E_{thr} = E_{\overline{\nu}_e} - 0.8$ MeV. After the thermalization of the neutron, it is captured by a proton releasing 2.2 MeV in gamma radiation, which exites the LS and causes the delayed signal. The measured energy spectrum of the reactor neutrinos will be fit assuming normal ordering (NO) or inverted ordering (IO). The difference of the minimal chi-square values between both fits is defined as the discriminator of the NMO, i.e., $\Delta\chi^2_{min}$. Figure 4 (Left) shows the expected sensitivity evolution to the NMO for both scenarios of NO and IO including statistical and systematic uncertainties. Therefore, JUNO can determine the NMO at a 3σ confidence level after about six years of data taking [3,10].

Besides, the sensitivity of JUNO for measuring several neutrino oscillation parameters has been investigated in [1]. It is expected that JUNO will measure the two 'solar' parameters, i.e., Δm^2_{21} and $\sin^2\theta_{12}$, and the 'atmospheric' mass splitting Δm^2_{31} with sub-perccent precision after six years of data taking as Figure 4 (Right) shows. It is also predicted that JUNO will already cross the current world-leading precision after the first 100 days [1]. Therefore, JUNO will contribute significantly to global tests of the unitarity of the neutrino mixing matrix.

3.2 Geoneutrinos

Geoneutrinos originate from radioactive decay chains of naturally abundant and long-lived isotopes inside Earth such as ^{238}U and ^{232}Th. The observation of geoneutrinos is a unique and non-invasive tool to study, e.g., the amount of radiogenic heat, the chemical composition or formation processes of the Earth. JUNO will measure around 400 events per year via IBD
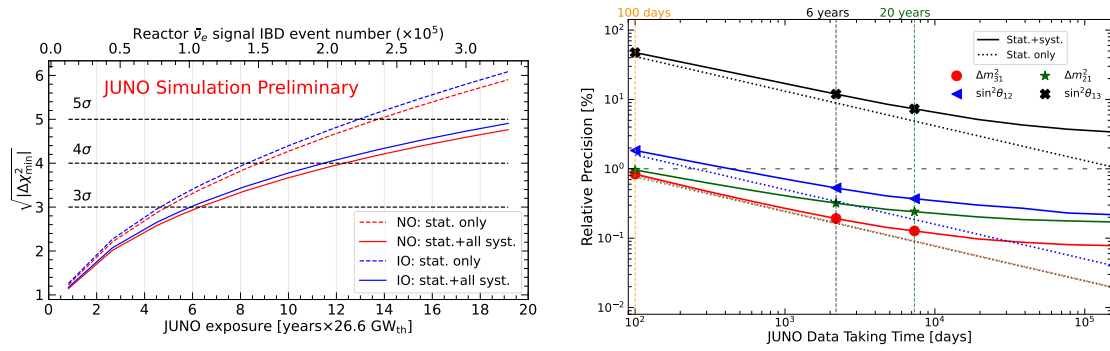
Figure 4: **Left:** Evolution of sensitivity for NO and IO [10]. **Right:** Evolution of relative precision for the oscillation parameters Δm_{31}^2, Δm_{21}^2, $\sin^2 \theta_{12}$ and $\sin^2 \theta_{13}$ [1].

significantly improving the statistics of the existing global geoneutrino event sample [2, 3].

3.3 Solar neutrinos

Solar neutrinos provide valuable information, e.g., about the solar metallicity or neutrino oscillations. They are produced as electron neutrinos along reaction chains of nuclear fusion processes in the core of the Sun. JUNO measures solar neutrinos via elastic neutrino scattering (ES), $\nu_e + e^- \rightarrow \nu_e + e^-$ and they are studied via neutrino spectroscopy. Sensitivity studies of ^{8}B solar neutrinos predict a precision of 5 %, 8 % and 20 % for their flux, $\sin^2 \theta_{12}$ and Δm_{21}^2, respectively [11, 12]. Sensitivity studies of ^{7}Be, pep and CNO solar neutrinos were conducted assuming several radiopurity scenarios of the LS. The precision on the fluxes can be improved in most cases [13].

3.4 Supernova neutrinos and multi-messenger trigger system

The observation of supernova burst neutrinos is a unique opportunity to study, e.g., stages and mechanisms of supernova (SN) explosions or search for collective neutrino oscillations. Assuming one nearby core-collapse supernova (CCSN) at a distance of 10 kpc, JUNO will detect large statistics of SN burst neutrinos in multiple-flavor detection channels, i.e., about 5,000 IBD events, about 2,000 all-flavor neutrino-proton ES events via $\nu + p \rightarrow \nu + p$, and about 300 neutral-current (NC) ES signals while CC and NC interactions on ^{12}C nuclei are also observable [3, 14]. Besides, an independent multi-messenger (MM) trigger system provides an ultra-low detection threshold of few tens of keV allowing to observe low-energy transient signals and to monitor CCSNe with an extended energy band. JUNO will play a major role in the global network of MM observatories and in the next-generation Supernova Early Warning System [3, 14]. Another objective is the search of the diffuse supernova neutrino background (DSNB), which is the cumulative neutrino flux from past supernovae in the visible Universe. The observation would provide information about the average CCSN energy spectrum, the cosmic star-formation rate or the fraction of black hole formation. JUNO could identify a few DSNB events per year via IBD within an energy window between around 10 MeV to 30 MeV defined by the IBDs of reactor and atmospheric neutrinos. Main background within this window are the NC interactions of atmospheric neutrinos, which can be effectively reduced by applying pulse shape discrimination. The discovery potential of the DSNB is estimated to 3 σ after three years of data taking while non-observation would significantly improve current limits and constrain the model parameter space [3, 15].

3.5 Atmospheric neutrinos

JUNO measures several atmospheric neutrinos per day below and within the GeV range. The reconstruction of atmospheric electron and muon neutrino energy spectra is expected to reach 10 % to 25 % precision with five years of data. Beyond that, detecting oscillated atmospheric neutrinos allows to investigate the octant of the mixing angle θ_{23} and to enhance the sensitivity of JUNO for the NMO by providing complementary inputs [3, 16]. Besides, JUNO will be able to detect the appearance of tau neutrinos ν_τ [17].

3.6 Proton decay

The observed matter-antimatter asymmetry in the Universe can be explained by baryon number violation, which is an inevitable consequence of Grand Unified Theories. JUNO is able to probe the possible proton decay channel $p \rightarrow \overline{\nu} + K^+$, which features a clear three-fold time-correlated scintillation signature due to the prompt signal of the kaon, a short delayed signal of its daughter and the late signal of the daughter's decay positron. JUNO will be competitive to world-leading lower limits on the proton lifetime by being sensitive to $> 9.6 \times 10^{33}$ years at 90 % C.L. after 10 years of data taking [3, 18].

4 Conclusion

JUNO is a next-generation large-scale neutrino observatory whose main goal is to determine the neutrino mass ordering with a 3σ significance after six years of data taking. Among other things, the study of several neutrino properties and neutrino sources, including the Sun, the Earth's interior, the atmosphere or core-collapse supernovae complement the rich physics program. The filling of the JUNO detector and the start of data taking are expected before the end of 2024.

Acknowledgements

M.R.S. wishes to thank the organizers of this conference and the JUNO collaboration for the opportunity and invitation to give this presentation. The JUNO collaboration is grateful for the ongoing cooperation from the China General Nuclear Power Group.

Funding information M.R.S. is supported by the German Collaborative Research Center "Neutrinos and Dark Matter in Astro- and Particle Physics" (SFB 1258) and the Deutsche Forschungsgemeinschaft (DFG) (FOR 5519). This work was supported by the Chinese Academy of Sciences, the National Key R&D Program of China, the CAS Center for Excellence in Particle Physics, Wuyi University, and the Tsung-Dao Lee Institute of Shanghai Jiao Tong University in China, the Institut National de Physique Nucléaire et de Physique de Particules (IN2P3) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, the Italian-Chinese collaborative research program MAECINSFC, the Fond de la Recherche Scientifique (F.R.S-FNRS) and FWO under the "Excellence of Science — EOS" in Belgium, the Conselho Nacional de Desenvolvimento Científico e Tecnològico in Brazil, the Agencia Nacional de Investigacion y Desarrollo and ANID — Millennium Science Initiative Program — ICN2019_044 in Chile, the Charles University Research Centre and the Ministry of Education, Youth, and Sports in Czech Republic, the Deutsche Forschungsgemeinschaft (DFG), the Helmholtz Association, and the Cluster of Excellence PRISMA$^+$ in Germany, the Joint Institute of Nuclear

Research (JINR) and Lomonosov Moscow State University in Russia, the joint Russian Science Foundation (RSF) and National Natural Science Foundation of China (NSFC) research program, the MOST and MOE in Taiwan, the Chulalongkorn University and Suranaree University of Technology in Thailand, University of California at Irvine and the National Science Foundation in U.S.A.

References

[1] A. Abusleme et al., *Sub-percent precision measurement of neutrino oscillation parameters with JUNO**, Chin. Phys. C **46**, 123001 (2022), doi:10.1088/1674-1137/ac8bc9.

[2] F. An et al., *Neutrino physics with JUNO*, J. Phys. G: Nucl. Part. Phys. **43**, 030401 (2016), doi:10.1088/0954-3899/43/3/030401.

[3] A. Abusleme et al., *JUNO physics and detector*, Prog. Part. Nucl. Phys. **123**, 103927 (2022), doi:10.1016/j.ppnp.2021.103927.

[4] A. Abusleme et al., *The JUNO experiment top tracker*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **1057**, 168680 (2023), doi:10.1016/j.nima.2023.168680.

[5] A. Abusleme et al., *Calibration strategy of the JUNO experiment*, J. High Energy Phys. **03**, 004 (2021), doi:10.1007/JHEP03(2021)004.

[6] A. Abusleme et al., *Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **988**, 164823 (2021), doi:10.1016/j.nima.2020.164823.

[7] P. Lombardi et al., *Distillation and stripping pilot plants for the JUNO neutrino detector: Design, operations and reliability*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **925**, 6 (2019), doi:10.1016/j.nima.2019.01.071.

[8] A. Abusleme et al., *The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS*, Eur. Phys. J. C **81**, 973 (2021), doi:10.1140/epjc/s10052-021-09544-4.

[9] A. Abusleme et al., *TAO conceptual design report: A precision measurement of the reactor antineutrino spectrum with sub-percent energy resolution*, (arXiv preprint) doi:10.48550/arXiv.2005.08745.

[10] J. Zhao, *JUNO status & prospects*, in *The XXX international conference on neutrino physics and astrophysics*, (2022), doi:10.5281/zenodo.6683749.

[11] A. Abusleme et al., *Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO*, Chin. Phys. C **45**, 023004 (2021), doi:10.1088/1674-1137/abd92a.

[12] J. Zhao et al., *Model-independent approach of the JUNO ^{8}B solar neutrino program*, Astrophys. J. **965**, 122 (2024), doi:10.3847/1538-4357/ad2bfd.

[13] A. Abusleme et al., *JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos*, J. Cosmol. Astropart. Phys., 022 (2023), doi:10.1088/1475-7516/2023/10/022.

[14] A. Abusleme et al., *Real-time monitoring for the next core-collapse supernova in JUNO*, J. Cosmol. Astropart. Phys., 057 (2024), doi:10.1088/1475-7516/2024/01/057.

[15] A. Abusleme et al., *Prospects for detecting the diffuse supernova neutrino background with JUNO*, J. Cosmol. Astropart. Phys., 033 (2022), doi:10.1088/1475-7516/2022/10/033.

[16] A. Abusleme et al., *JUNO sensitivity to low energy atmospheric neutrino spectra*, Eur. Phys. J. C **81**, 887 (2021), doi:10.1140/epjc/s10052-021-09565-z.

[17] S. A. Meighen-Berger, J. F. Beacom, N. F. Bell and M. J. Dolan, *New signal of atmospheric tau neutrino appearance: Sub-GeV neutral-current interactions in JUNO*, Phys. Rev. D **109**, 092006 (2024) doi:10.1103/PhysRevD.109.092006.

[18] A. Abusleme et al., *JUNO sensitivity on proton decay $p \rightarrow \overline{\nu}K^+$ searches**, Chin. Phys. C **47**, 113002 (2023), doi:10.1088/1674-1137/ace9c6.