PROCEEDINGS OF SCIENCE

Physics prospects of JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kiloton multi-purpose liquid scintillator detector located in South China. With detector construction complete, JUNO is currently taking data during the water-filling phase, with full liquid scintillator operations in the second half of 2025. JUNO's primary goal is to determine the neutrino mass ordering, with an expected significance of 3–4 sigma in about six years, by observing the modulations in the energy spectrum of reactor electron antineutrinos from two nuclear power plants at about 53 km. Additionally, JUNO's unprecedented energy resolution and target volume, will enable sub-percent precision measurements of oscillation parameters with just a few months of data and the observation of neutrinos from natural sources, including atmospheric, solar, astrophysical, and geo-neutrinos. As JUNO prepares for full operation, this talk will explore its physics potential and the scientific opportunities ahead.

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1. Introduction

One of the most important open questions in neutrino physics is the determination of the neutrino mass ordering (NMO), i.e., whether the third mass eigenstate is the heaviest or the lightest. The Jiangmen Underground Neutrino Observatory (JUNO) [1] is a 20 kiloton liquid scintillator detector installed in South China, 700 m underground. It is located at about 53 km from two nuclear power plants, the optimal position for the determination of the NMO through the interplay between solar and atmospheric oscillations. Its large size, strategic position, and unprecedented performance make it an effective multi-purpose experiment: besides electron antineutrinos from nuclear reactors, JUNO will detect neutrinos of all flavors from natural sources (solar, atmospheric, astrophysical, and geo-neutrinos) and explore physics beyond the Standard Model. JUNO is expected to contribute with leading measurements to various areas of neutrino physics for the next decade. In this proceeding, a selected list of topics will be presented, while a more extensive description of the JUNO physics case can be found in [1].

2. JUNO detector

To achieve its scientific goals, JUNO features multiple detector systems (Fig. 1). The experiment consists of an acrylic sphere of 35.4 m diameter (central detector, CD) filled with 20,000 tons of liquid scintillator and instrumented with 17,600 20-inch PMTs (LPMT) and 25,600 3-inch PMTs (SPMT). The CD is immersed in a Water Cherenkov Detector (WCD) filled with 35 kilotons of ultra-pure water and instrumented with 2,400 LPMTs. A three-layer top-tracker (TT), consisting of plastic-scintillator strips, acts as an active muon veto, covering about 60% of the CD surface projection. Moreover, the detector construction and installation were performed under strict radiopurity requirements. The detector construction was completed in December 2024, and the filling of the CD and WCD with water and liquid scintillator was completed in August 2025. A status report on the detector construction and filling can be found in [2] at this conference.

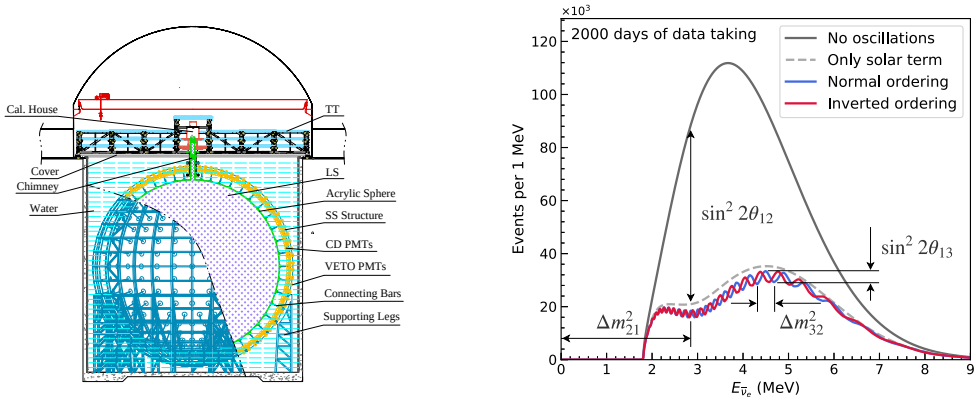

Figure 1: Left: Schematic view of the JUNO detector and its main components. Right: The expected antineutrino energy spectrum – under the assumption of perfect resolution – with and without oscillation, and for normal ordering (NO, red) and inverted ordering (IO, blue), assuming 6 years of data taking [1].

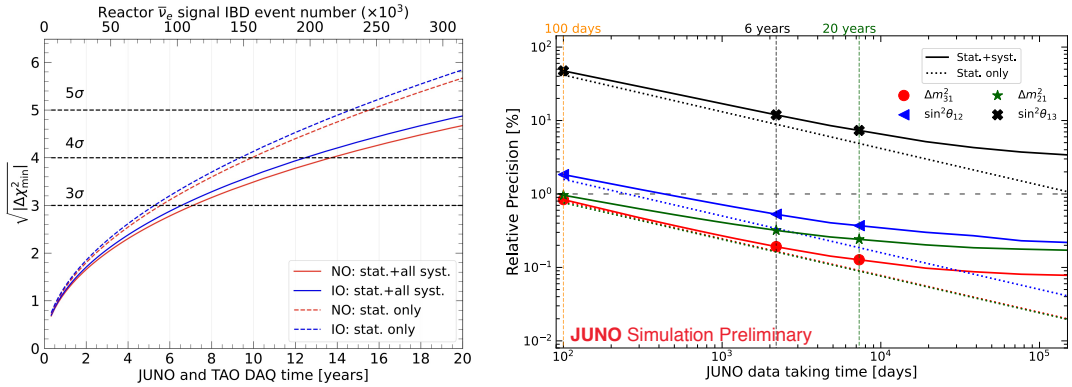

Figure 2: Left: NMO discriminator $\Delta\chi^2_{\rm min}$ as a function of JUNO and TAO data-taking time for NO and IO. Horizontal black dashed lines represent 3σ, 4σ, and 5σ significances. Solid lines include systematic uncertainties, dashed lines are statistical-only. Right: Relative precision of the oscillation parameters as a function of JUNO data-taking time. Sub-percent precision can be achieved after six years for Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} [4].

3. Oscillation physics with neutrino from nuclear reactors

Differently from long-baseline neutrino experiments (accelerator and atmospheric neutrinos), JUNO allows a unique NMO determination based on a quasi in-vacuum measurement, with negligible dependence on matter effects and the unknown CP-violating phase. As shown in Fig. 1 (right), the NMO determination relies on the precise measurement of the electron antineutrino spectrum and the reconstruction of the specific pattern produced by the interplay of two oscillation modes: slow (solar) and fast (atmospheric) oscillations. A challenging energy resolution of 3% at 1 MeV and an energy scale accuracy better than 1% are required, implying a large detector volume, high optical coverage, and high light collection efficiency. The details of the analysis are available in [3].

The NMO sensitivity is shown in Fig. 2 (left). The NMO discriminator $\Delta\chi^2$ is shown as a function of JUNO data-taking time for both Normal Ordering (NO, red) and Inverted Ordering (IO, blue), for the case including systematic uncertainties (solid lines) or statistical only (dashed lines). A reactor duty cycle of 11/12 months is considered in the conversion of exposure to data-taking time. After 7.1 years, JUNO can determine the neutrino mass ordering with 3σ significance if NO is true. Besides the NMO, JUNO measurements of the reactor neutrino spectra will significantly improve the precision of the solar oscillation parameters Δm^2_{21}, $\sin^2\theta_{12}$, and the mass splitting term Δm^2_{31}. The precision achieved by JUNO for the four oscillation parameters is shown in Fig. 2 (right) as a function of data-taking time. After six years, JUNO can reach sub-percent precision on three of the oscillation parameters.

3.1 Atmospheric neutrinos

Atmospheric neutrinos, of all flavors, are produced by cosmic rays in the Earth's atmosphere. JUNO focuses mostly in the low energy part of the spectrum – from a few MeV up to about 20 GeV – to obtain Full Contained events (and consequently a calorimetric measurement of the visible energy). In this range the dominant interaction is the neutrino-nucleon scattering. The

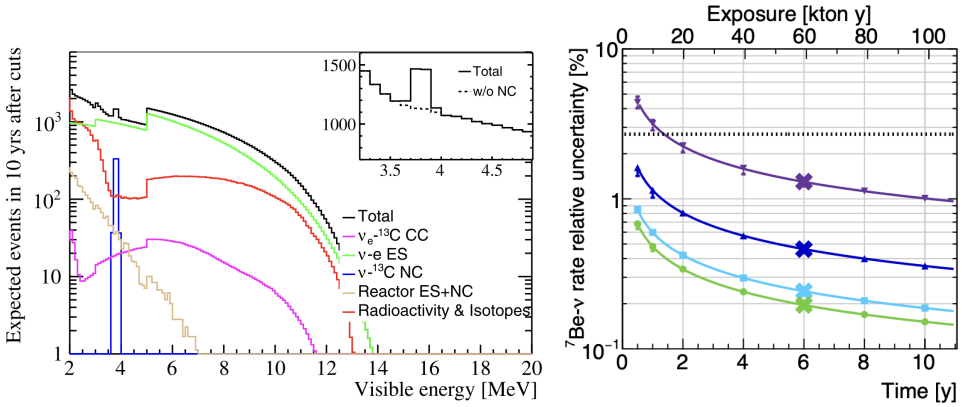

Figure 3: Left: Expected visible energy spectra for all single-event sources for 10 yr of data taking above 2 MeV [7]. Right: relative uncertainties for ^{7}Be as a function of exposure. Different background scenarios are shown. Dotted horizontal lines indicate Borexino uncertainties [10].

discrimination between electron and muon neutrinos is based on the different hit time pattern [5]. Moreover, as atmospheric neutrinos traverse the Earth before reaching the detector, their oscillations are modified by matter effects, which depend on the NMO. JUNO can therefore probe the NMO by measuring the energy and angular distributions of upward-going atmospheric neutrinos, with the strongest sensitivity in the 1–10 GeV range [6]. Preliminary studies indicate that JUNO could achieve an NMO sensitivity of roughly 1 σ after six years of data taking, using atmospheric neutrinos only. This complementary measurement is very promising to boost the overall JUNO sensitivity to NMO.

3.2 Solar neutrinos

Solar neutrinos are produced as electron neutrinos along reaction chains of nuclear fusion in the Sun. JUNO can detect MeV-scale neutrinos—particularly those from ^{8}B, ^{7}Be, pep, and CNO reactions—mainly via elastic scattering (ES) on electrons in the liquid scintillator. Achieving an ultra-low background is essential, including careful material selection and optimized background rejection, as detailed in [7, 10, 11]. The expected number of events after 10 years in the energy range above 2 MeV (^{8}B neutrinos) is shown in Fig. 3 (left).

Within the standard three-flavor oscillation framework, JUNO can measure $\sin^2\theta_{12}$ and Δm^2_{21} through a combined fit of the ES rate, energy spectrum, and day–night asymmetry. Although statistics are limited, after ten years the expected precision is comparable to current global solar fits [9] and may reveal discrepancies with reactor neutrino results [8]. At low energy (E>0.45 MeV), JUNO's excellent energy resolution will allow isolation of the ^{7}Be shoulder in the scattered electron energy spectrum. Figure 3 shows the precision achievable for ^{7}Be as a function of exposure and radiopurity scenarios, demonstrating that JUNO will surpass Borexino in a few years of operation[1].

[1] Similar plots for pep, and CNO neutrino fluxes are available in [10].

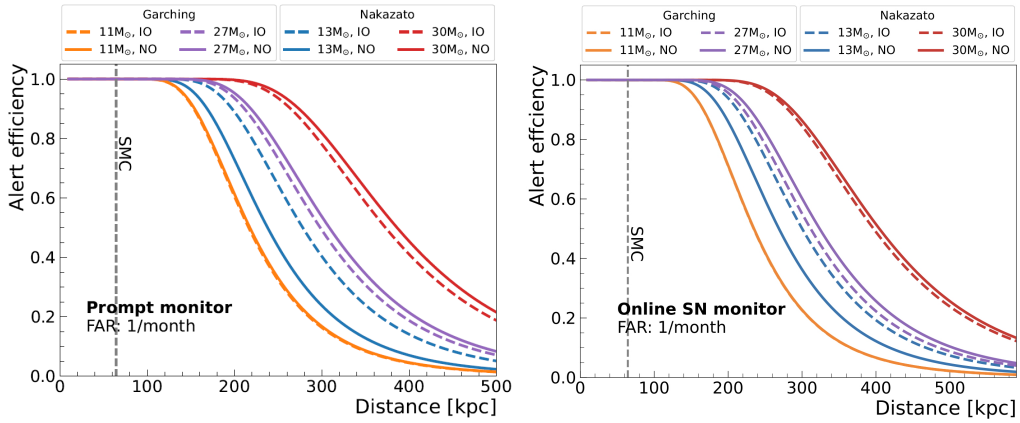

Figure 4: Left: Expected alert efficiency for the prompt monitor for SN neutrinos of Nakazato [13] and Garching [14] models at different distances, assuming a False Alert Rate of 1/month. Right: Expected alert efficiency for the online monitor. From [12].

4. Supernova neutrinos

Core-collapse supernovae (CCSN) are explosions of massive stars at the end of their life and one of the most energetic phenomena in the Universe, but rare in our Galaxy (∼1–3 per century). The observation of neutrinos from CCSN provides unique information on explosion mechanisms and neutrino properties. Moreover, neutrinos arrive hours before the electromagnetic signal, enabling early alerts for telescopes worldwide. JUNO can detect around 10,000 neutrinos of all flavors[2], mostly through Inverse Beta Decay and electron scattering for a CCSN at 10 kpc [1].

A redundant monitoring system is implemented. The "prompt monitor" works at the electronics level, providing alerts in a few ms depending on model and CCSN distance. The "online monitor" runs at the DAQ level, offering more precise event selection and energy reconstruction but with a longer alert time. A complementary Multi-Messenger (MM) system provides independent alerts with a lower energy threshold $O(10$ keV), capturing low-energy transients and the neutronization ν_e burst. Fig. 4 shows the alert efficiency as a function of CCSN distance for different models, under the assumption of a False Alert Rate (FAR) of 1 per month. A similar study done for pre-SN neutrinos highlights a maximum alert distance of about 2 kpc. More details on the alert systems and their performance for different FAR assumptions and different models can be found in [12]. The JUNO collaboration participates to the SNEWS 2.0 (SuperNova Early Warning System) network for the alerts sharing [15].

5. Conclusions

JUNO is a large-scale neutrino observatory whose main goal is to determine the neutrino mass ordering with 3 σ significance after six years of data taking. JUNO will also lead in the measurement of oscillation parameters (Δm^2_{21}, $\sin^2\theta_{12}$, Δm^2_{31}) at the sub-percent level and in the detection of neutrinos from natural sources. The study of neutrino properties and sources—including the Sun,

[2]Depending on the CCSN model and progenitor mass

the Earth's interior, the atmosphere, and core-collapse supernovae—complements JUNO's rich physics program. The filling of the JUNO detector has been completed in August 2025 and data taking is ongoing.

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