PROCEEDINGS OF SCIENCE

JUNO Experiment: Advancing the Next Generation of Reactor Neutrino Research

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Since the discovery of neutrinos, nuclear reactor has played a major role in understanding neutrino physics, from the observation of neutrino oscillations with the precise measurement of Δm_{21} and θ_{12}, to the more recent breakthrough precise measurement of θ_{13} by the Daya Bay, Double Chooz and RENO. With the Jiangmen Underground Neutrino Observatory (JUNO), reactor neutrino physics is entering a new era in terms of precision and physics reach. Situated 52.5 km from two nuclear power plants within a newly established 700-meter-deep underground laboratory, JUNO aims to determine neutrinos mass ordering by precisely measuring the energy spectrum of reactor neutrinos. In addition, it will measure, with sub-percent precision, most of the neutrino oscillation parameters. Thanks to its excellent characteristics in terms of an unprecedented active mass and excellent energy resolution, the JUNO physics program comprises also solar neutrinos, atmospheric neutrinos, supernova neutrinos, and geoneutrinos, as well as beyond standard model physics topics such as nucleon decay. This paper will present the JUNO experiment in the context of current reactor neutrino experiments and upcoming long-baseline neutrino oscillation programs, highlighting the complementarity and synergies between JUNO and these initiatives in understanding the fundamental properties of neutrinos.

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1. Introduction

After the initial discovery of the atmospheric neutrino anomaly by the Kamiokande experiment in the 1980s, it took nearly two decades to confirm that neutrino oscillations are a fundamental phenomenon of nature, influencing not only particle physics, but also astrophysics and cosmology. Over the past two decades, significant progress has been made in understanding neutrino oscillations through extensive experimental and theoretical investigations.

Thanks to a wide variety of experiments involving atmospheric, solar, reactor, and accelerator neutrinos, we now have a comprehensive picture of neutrino oscillations as a three-flavor phenomenon. These oscillations are governed by two distinct mass square differences Δm^2_{21} and Δm^2_{32}, three mixing angles θ_{12}, θ_{13}, and θ_{23}, and possibly a charge-parity (CP) violating phase δ_{CP}.

Currently, the most precise measurements of neutrino oscillation parameters come from a specific set of experiments, each of which dominates the accuracy of a particular parameter. In the so-called solar sector (θ_{12} and Δm^2_{21}), the mass-square difference Δm^2_{21} is determined with less than 3% uncertainty, primarily by the KamLAND long-baseline reactor antineutrino experiment. Meanwhile, the mixing angle $\sin^2\theta_{12}$ is measured with approximately 4% precision through a combination of solar neutrino experiments.

In the atmospheric sector (θ_{23} and Δm^2_{32}), the mass-square difference Δm^2_{32} (or equivalently Δm^2_{31}) and the mixing angle $\sin^2\theta_{23}$ are predominantly measured by the disappearance of muon neutrinos ν_μ and antineutrino $\bar{\nu}_\mu$ in accelerator-based experiments, including MINOS, NOvA and T2K. These experiments achieve a precision better than 1.5% for Δm^2_{32} and about 4% for $\sin^2\theta_{23}$.

The mixing angle $\sin^2\theta_{13}$, which connects the solar and atmospheric sectors, is determined by short-baseline reactor antineutrino disappearance experiments, specifically Daya Bay, RENO, and Double Chooz, achieving a precision of around 3%. For a complete review, see [1].

The determination of the CP-violating phase, δ_{CP}, remains a significant challenge in neutrino physics. Current measurements from the T2K and NOvA experiments exhibit slight tensions, suggesting inconsistencies that are unlikely to be fully resolved without the enhanced sensitivity of next-generation long-baseline neutrino experiments, such as DUNE and Hyper-Kamiokande.

An important unresolved issue that impacts the precision of several oscillation parameters is the question of Neutrino Mass Ordering (NMO): whether the neutrino mass hierarchy follows a normal ($\Delta m_{31} > 0$), or inverted ($\Delta m_{31} < 0$) ordering (NO, IO). This question is crucial for advancing our understanding of neutrino physics and guiding future experimental efforts.

The relatively large value of θ_{13} provides significant opportunities to investigate NMO using a variety of approaches. These include medium baseline ($\sim$ 50 km) reactor antineutrino oscillation experiments ($\bar{\nu}_e \rightarrow \bar{\nu}_e$), such as JUNO [2], as well as long baseline accelerator (anti)neutrino oscillation experiments ($\nu_\mu \rightarrow \nu_e$), such as NO$\nu$A [3] and DUNE [4]. Furthermore, atmospheric (anti)neutrino oscillation experiments, including IceCube-PINGU [5], KM3Net [6], DUNE [4], and Hyper-K [7], contribute to the exploration of the NMO.

Accelerator and atmospheric neutrino experiments determine the NMO by exploiting the matter effect [8, 9] in neutrino oscillations, which arises from the charge-current interaction between ν_e ($\bar{\nu}_e$) and electrons in the Earth's matter. In contrast, JUNO is uniquely optimized to determine the NMO by precisely analyzing the oscillation interference pattern resulting from the interplay between Δm^2_{31} and Δm^2_{32} [10] in nearly-vacuum oscillation conditions. Notably, JUNO's sensitivity [11] to

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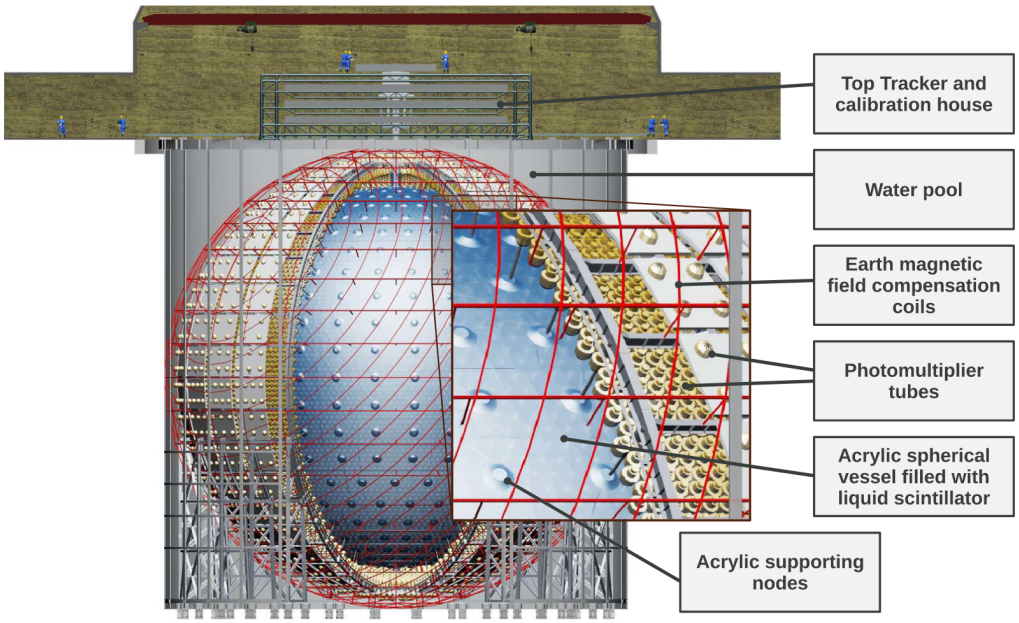

Figure 1: JUNO detector components from [2]

the NMO is independent of the unknown CP-violating phase and the θ_{23} octant, making it a crucial complement to other neutrino experiments.

2. The JUNO detector

The JUNO detector is composed of three primary components: the central detector (CD), an instrumented water pool (WP) acting as Cherenkov detector, and the Top Tracker (TT) placed above the CD and the WP. The CD is a liquid scintillator detector (LS) with a mass of 20 kilotons, enclosed within a spherical acrylic vessel with a diameter of 35.4 meters [2]. The LS is composed of linear alkylbenzene (LAB) serving as the scintillation solvent, 2,5-diphenyloxazole (PPO) as the primary fluor, and p-bis-(o-methylstyryl)-benzene (bis-MSB) as the wavelength shifter [2, 12, 13]. This mixture is specifically tailored to optimize both light emission and transparency. Scintillation light generated through interactions within the LS is detected by 17,612 20-inch large PMTs (LPMTs) [14] and 25,600 3-inch small PMTs (SPMTs) [15]. These are mounted on a stainless steel (SS) framework and framed by Earth's magnetic field compensation coils. Two sizes of PMTs are employed to support a dual calorimetry strategy, which allows for (i) handling a wide range of signal dynamics, (ii) obtaining enhanced photocoverage, and (iii) correcting non-linearities introduced by the PMTs and electronic readout systems [16]. This arrangement aims to produce an energy resolution of 2.95% at 1 MeV [17].

The CD is immersed in a cylindrical water Cherenkov detector (WP) filled with ultrapure water and is instrumented with 2,400 20-inch PMTs. The WP acts as an active veto for cosmic muons and as a passive shield against external radioactivity and cosmogenic neutrons.

Above the CD and the WP lies the TT [18], designed to provide precise tracking of cosmic muons entering the detector from above. The TT consists of 496 plastic scintillator strip modules,

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each with a length of 6.86 meters, organized into two orthogonal layers to offer tracking data in two dimensions. Each strip is read out on both sides by wavelength-shifting fibers coupled to PMTs. The TT, which was initially utilized in the OPERA experiment, is mainly employed in JUNO to reconstruct and extrapolate cosmic muons to the CD and WP, thereby enhancing the tagging and suppression of the cosmogenic background.

To achieve the required energy resolution and energy scale calibration needed for NMO measurement, JUNO requires a precise calibration of its energy response [2, 19]. This is accomplished through a comprehensive calibration system that utilizes a range of radioactive sources, including gamma and neutron sources, cosmogenic ^{12}B, and a pulsed UV laser. The calibration strategy relies critically on the deployment of radioactive sources at multiple positions throughout the CD to precisely map and correct spatial nonuniformities in detector response. This comprehensive coverage is achieved through three complementary systems: a vertical spooling mechanism, a guide tube network attached to the acrylic sphere, and an automated positioning system combining cable loops and a remotely operated vehicle (ROV).

Ensuring high radiopurity of the LS is crucial for JUNO, especially for detecting low-energy neutrinos from the Sun [20] and supernovae. The LS undergoes several purification stages, including alumina column chromatography, distillation, water extraction, and steam stripping [21]. The online detector internal radioactivity investigation system (OSIRIS) [22] is used to confirm the radiopurity of a 15% subsample of LS prior to filling.

2.1 Taishan Antineutrino Observatory

The Taishan Antineutrino Observatory (TAO) [23] is a high-precision detector designed to measure reactor antineutrinos with exceptional energy resolution. Located 44 meters from one of the Taishan nuclear reactor cores, TAO serves as a near detector for the JUNO experiment, providing a reference spectrum for accurate neutrino oscillation analysis.

The detector consists of a spherical acrylic vessel filled with a liquid scintillator (LS) doped with gadolinium to enhance neutron capture efficiency. It is equipped with high-density silicon photomultiplier (SiPM) arrays, enabling an unprecedented 95% photo-coverage and an energy resolution of better than 2% at 1 MeV.

3. JUNO Osciallation physics

JUNO's outstanding detection capabilities enable investigations across multiple neutrino sources, including solar neutrinos, terrestrial antineutrinos (geoneutrinos), burst neutrinos from core-collapse supernovae, and diffuse supernova neutrino background. Nevertheless, JUNO main focus is the study of neutrino oscillations with reactor antineutrinos.

The strategic placement of JUNO at a baseline of 52.5 kilometers from the Taishan and Yangjiang nuclear power plants, with a total thermal power of 26.6 $GW_{th}h$, provides an ideal setting to determine NMO and measure, at a subprecent level, three of the six parameters that describe the neutrino oscillation phenomena, namely Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}.

Reactor antineutrinos are detected via Inverse Beta Decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The e^+ produced in IBD events quickly annihilates with an electron, producing two 0.511 MeV gammas that create the prompt signal. The neutron produced in the interaction is thermalized

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in a few microseconds and is subsequently captured predominantly by a free proton in the LS, emitting 2.22 MeV gammas. In inverse beta decay (IBD) events, the majority of the antineutrino's energy is transferred to the positron, enabling the reconstruction of the antineutrino energy from the measured prompt energy. Specifically, the antineutrino energy can be approximated as $E_{\bar{\nu}_e} \approx E_{prompt} + 0.78$ MeV, where the offset accounts for the neutron-proton mass difference. Figure 2 illustrate the impact of neutrino oscillations on the antineutrino energy spectrum at the JUNO site, emphasizing the way various oscillation parameters are reflected in the spectrum.

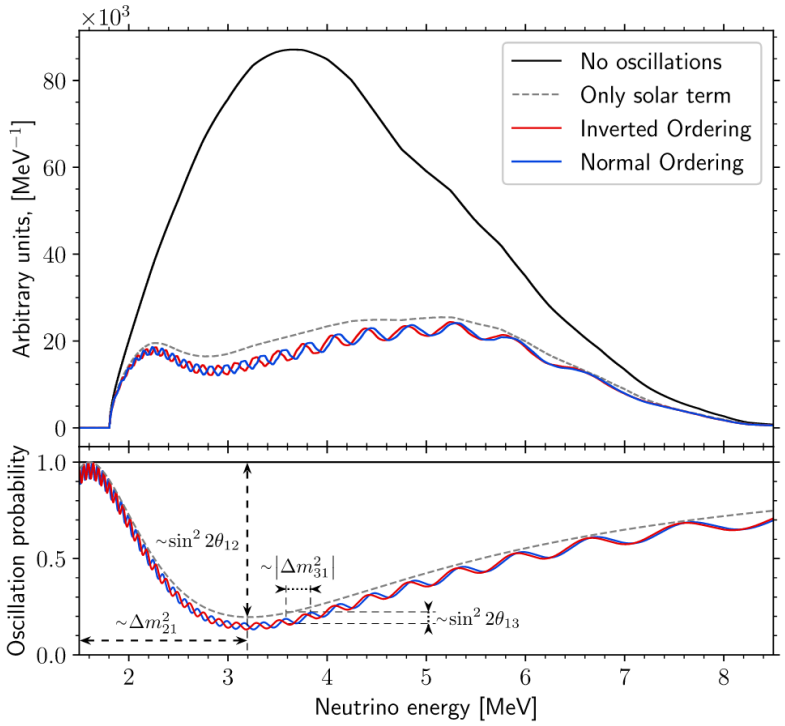

Figure 2: Impact of neutrino oscillation on the reactor antineutrino energy spectrum at the JUNO site [11].

The IBD reaction produces a characteristic double signature, enabling efficient signal-to-background discrimination. Major background sources include geoneutrinos, long-lived cosmogenic isotopes such as ^{9}Li and ^{8}He, as well as accidental coincidences predominantly arising from radioactive contamination. Figure 3 presents the reconstructed prompt energy spectrum, accounting for all detector effects, under both the Normal Ordering (NO) and Inverted Ordering (IO) hypotheses. The figure displays the reactor antineutrino signal along with all residual background contributions.

4. JUNO Expected Sensitivity to Oscillation Parameters and NMO

JUNO will measure Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} with unprecedented precision [24]. Figure 4 show the expected precision on the oscillation parameters as a function of the JUNO exposure. Within the first 100 days of running, JUNO will improve our current knowledge of Δm^2_{21}, $\sin^2\theta_{12}$,

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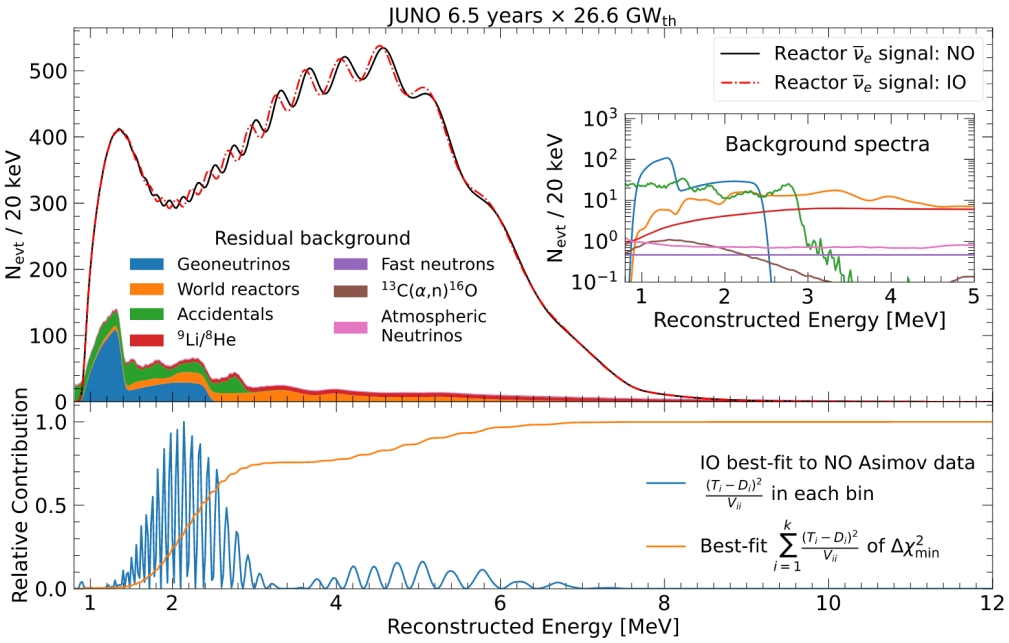

Figure 3: Top: Reconstructed energy spectra of JUNO in both the NO and IO scenarios without any statistical or systematic fluctuations. Bottom: Relative contribution to the $\Delta\chi^2$ and cumulative $|delta\chi^2$ obtained when fitting the IO spectrum with the NO hypothesis. For mode details see [11].

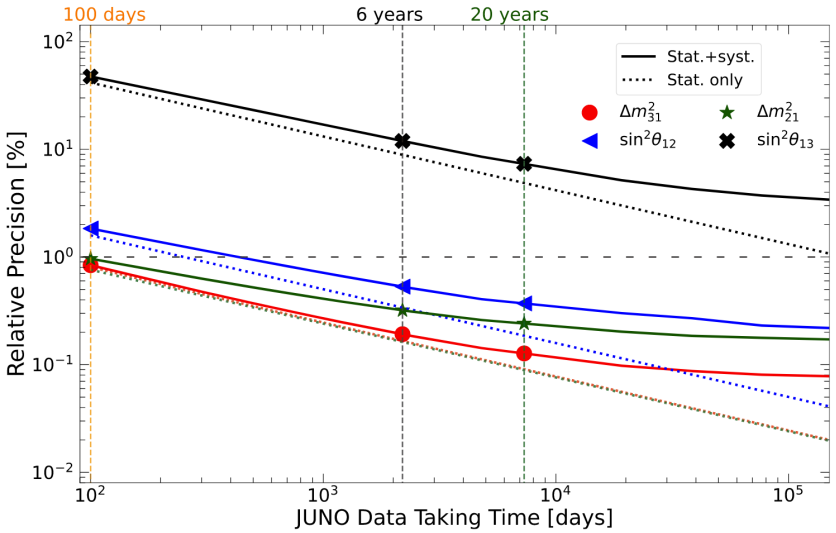

Figure 4: Relative precision on oscillation parameters as a function of JUNO exposure [24].

and Δm^2_{31}, and after 6 years, all parameters will be measured with precision better than 0.6%, potentially achieving precision near the permille level for Δm^2_{31}.

JUNO will determine neutrino mass ordering (NMO) by analyzing the rapid oscillation pattern resulting from the fine interaction between the two mass square differences Δm^2_{31} and Δm^2_{32}. Recently JUNO updated the sensitivity on NMO considering the join fit of JUNO and TAO data [11]. The

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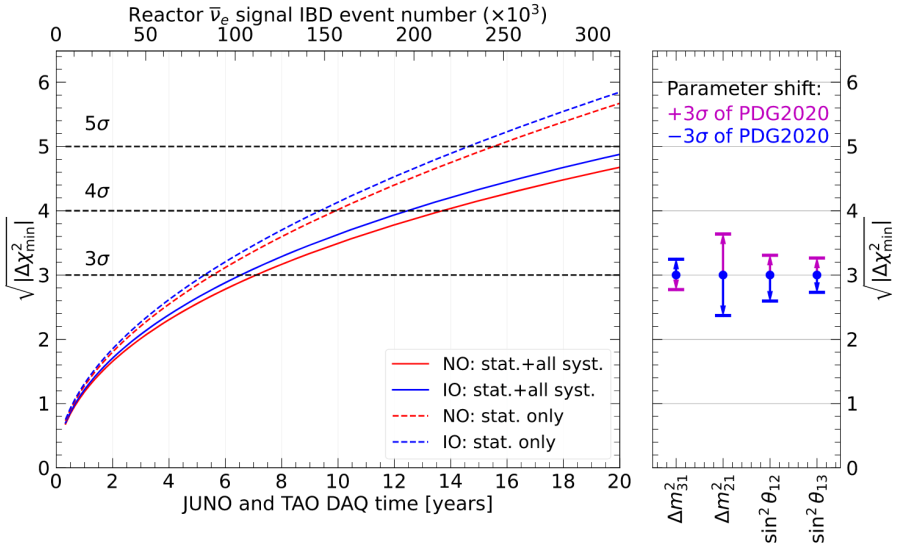

Figure 5: NMO median sensitivity as a function of JUNO exposure [11].

sensitivity reached by JUNO as a function of time is reported in Figure 5. Depending on mass ordering, normal or inverted ordering, JUNO can reach a 3 σ median sensitivity after 6.5 or 7.1 years, respectively [11].

5. Status of JUNO detector

At the time of writing this paper, the construction of the JUNO detector is completed and is now in the phase of filling the CD and WP. The liquid filling process will be carried out in two stages. During the first two months, the inner and outer spaces of the acrylic sphere will be filled with ultrapure water. During the following six months, the ultrapure water inside the acrylic sphere will be replaced by a liquid scintillator. Data collection is expected to start in August 2025.

6. Conclusions

The JUNO experiment, which will start the data taking in the next few month, marks a new era for reactor neutrino experiments and liquid scintillator detectors. The unprecedented scale of the detector, combined with its exceptional energy resolution over such a large volume, will enable a comprehensive and far-reaching physics program. In particular, JUNO will provide world-leading measurements of Δm^2_{21}, θ_{12} and Δm^2_{31} , well below the percent precision, and reach a 3σ median sensitivity to neutrino mass ordering after 6.5 or 7.1 years of exposure, whether the mass ordering is normal or inverted, respectively.

In the coming year, next generation long baseline neutrino beam experiments, DUNE and Hyper-K, will also measure, alone or in combination with atmospheric neutrino data, the NMO exploiting mater effect in electron (anti-)neutrino appearance channel. The complementary experimental approaches, vacuum oscillations measured by JUNO and matter-induced oscillations

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observed in LBνL accelerator experiments, are crucial for cross-validation and theoretical consistency. The comparison between these independent methods not only enhances the robustness of the NMO determination but also provides stringent constraints on the underlying neutrino oscillation framework.

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