PROCEEDINGS OF SCIENCE

Status and Astrophysical Potentials of JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose observatory under construction in China. The JUNO detector consists of a 20 kton liquid scintillator target monitored by about 18k 20-inch Photomultiplier Tubes (PMTs) and about 26k 3-inch PMTs. This detector is strategically located 53 km from the Taishan and Yangjiang Nuclear Power Plants in order to primarily determine the neutrino mass ordering and to precisely measure several oscillation parameters. In this talk, after a short introduction on the detector design and the construction status, I will discuss the physics potential of JUNO, with a focus on astrophysical neutrinos and multi-messenger observations.

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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose liquid scintillator detector with an expected energy resolution of $3\%/\sqrt{E[\mathrm{Mev}]}$. It is currently under construction in a 700 m underground laboratory located in Jiangmen city, Guangdong province in the south of China. The primary objectives of JUNO are to determine the neutrino mass ordering (NMO) and precisely measure the oscillation parameters [1]. The schematic design of the JUNO central detector, as shown in Figure 1, features high optical coverage and provides a significant amount of data for achieving the physics goals [1].

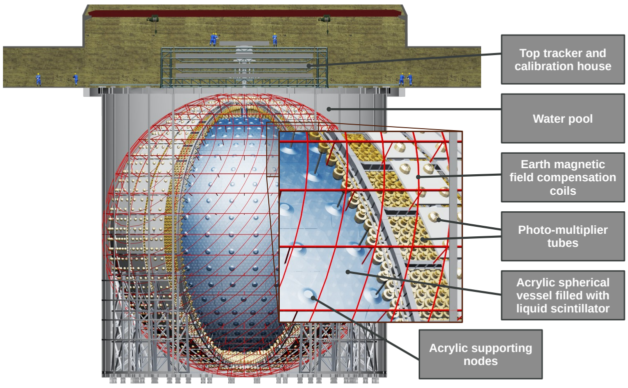


Figure 1: The JUNO detector schematic view. The liquid scintillator in the acrylic sphere is surrounded by 20-inch and 3-inch PMTs [1].

In addition to its significant contributions to neutrino physics, including the determination of neutrino mass ordering [2] and precision measurement of oscillation parameters [3], JUNO also serves as a multi-purpose observatory capable of detecting atmospheric neutrinos [4], solar neutrinos [5–7], supernova neutrinos [8, 9], and geo-neutrinos [10].

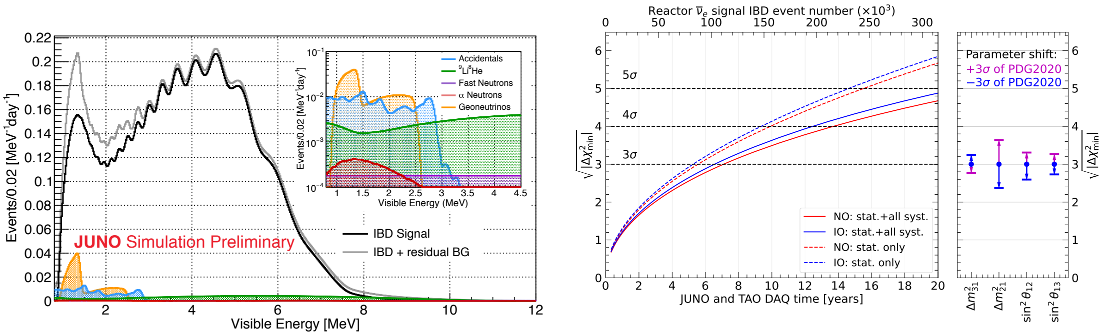
This presentation will report the JUNO NMO determination and precision measurement of oscillation parameters using reactor antineutrinos. In addition, the experiment's physics potential will be explored, with a particular focus on astrophysical neutrinos and multi-messenger observations.

2. Detector construction status

The JUNO detector [10, 11] is currently being constructed in an underground laboratory beneath Dashi Hill in Guangdong Province, South China. With a 650 m rock overburden (1800 m water equivalent), the cosmic muon flux is effectively suppressed to $4.1\times10^{-3}/(\mathrm{s}\cdot\mathrm{m}^2)$. A 20 kton liquid scintillator [12] target, consisting of ~88% carbon and ~12% hydrogen by mass, is contained in a 12-cm thick acrylic sphere with a 35.4 m inner diameter. In order to determine the NMO by precisely measuring the neutrino oscillation pattern, it is crucial to achieve an energy resolution better than 3% at 1 MeV, which is unprecedented for a detector of this type. The acrylic sphere is surrounded by 17,612 large 20-inch high quantum efficiency PMTs, referred to as LPMTs, and 25,600 small 3-inch PMTs, referred to as SPMTs, yielding a total 78% photo-cathode coverage. An ultra-pure water buffer with a minimal thickness of ~1.5 m fills the volume between the acrylic and the LPMT photocathode. This center detector (CD) is fully surrounded by an ultra-pure water Cherenkov detector that serves as an active veto for cosmic muons and as a passive shield against external radioactivity and neutrons from cosmic rays. The minimal thickness of the water detector is 2.5 m. The cosmic muon veto system is supplemented with an external muon tracker consisting of three layers of plastic scintillator refurbished from the OPERA experiment [13] located at the top, providing a muon track angular reconstruction precision of 0.20° [14]. This system [14] covers about 60% of the surface above the water pool.

3. Reactor antineutrinos

The primary signal for oscillation physics at JUNO is provided by the antineutrinos emitted from the reactors in close proximity to the experiment. These reactors are commercial light-water reactors, with over 99.7% of the antineutrinos originating from the fission of the isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. JUNO detects the reactor electron antineutrinos through the inverse beta decay (IBD) interaction: $\bar{\nu}_e + p \to e^+ + n$. In this process, the $\bar{\nu}_e$ interacts with a proton in the liquid scintillator (LS), resulting in the creation of a positron (e^+) and a neutron (n). The positron promptly deposits its energy and annihilates into two 0.511-MeV photons, generating a prompt signal. Subsequently, the neutron, after scattering in the detector for approximately 200 μs, is captured by hydrogen (approximately 99%) or carbon (approximately 1%), leading to the production of gammas with energies of 2.22 MeV or 4.95 MeV, respectively. The capture of the neutron produces a delayed signal.



(a) (b)

Figure 2: (a): The expected reactor antineutrino IBD signal and background spectra at JUNO [3]. (b): The NMO discriminator $\Delta\chi^2_{\min}$ as a function of JUNO and TAO data taking time for both the IO (red) and IO (blue) [2].

3.1 Neutrino mass ordering determination

To obtain the JUNO sensitivity, an Asimov data set, following the processes above under either normal ordering or inverted ordering hypothesis, was generated. A chi-square was obtained by fitting to an Asimov data with the assumptions of both normal and inverted ordering and take the difference of minima in 1 as a measure of NMO sensitivity [2].

$$\Delta\chi^2_{\text{NMO}} = \left|\chi^2_{\text{min}}(\text{NO}) - \chi^2_{\text{min}}(\text{IO})\right|, \tag{1}$$

where $\chi^2_{\text{min}}(\text{NO})$ and $\chi^2_{\text{min}}(\text{IO})$ are the minima of the chi-square function under the NO and IO hypothesis, respectively. We find that the median sensitivity of JUNO on determining the NMO would be larger than 3σ for around 6 years of data taking [2].

3.2 Precision measurement of oscillation parameters

The precision measurement of the oscillation parameters plays a vital role in neutrino physics. With a large number of reactor antineutrinos and excellent detector performance, JUNO will be able to measure the neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to an unprecedented precision of better than 1%. Figure 3 shows the time evolution of the JUNO precision sensitivity, which indicates the precision of oscillation parameters will come to the sub-percent era after about one year of data taking of JUNO [3].

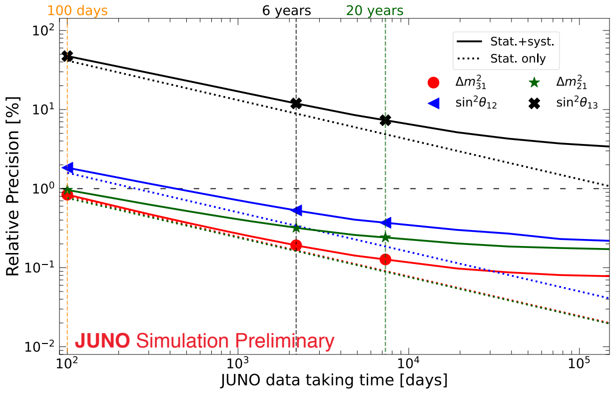


Figure 3: Relative precision of oscillation parameters as a function of JUNO data taking time. The dashed and solid lines are the sensitivity of considering only statistical uncertainty and all uncertainties, respectively [3].

4. Atmospheric neutrinos

Neutrinos produced in the interactions of cosmic rays with the Earth's atmosphere can be also detected by JUNO, whose large size allows to reconstruct these events at the $\mathcal{O}$(GeV) energy range [4]. The energy spectrum of atmospheric neutrinos can return many information about the production mechanisms. Moreover, it can help improving theoretical predictions in the multi–MeV region. Figure 4 shows the expected JUNO sensitivity towards the atmospheric ν_e and ν_μ fluxes in the [0.1 - 10] GeV range, assuming an exposure of 5 years and the HKKM14 model [15] as reference, also shown on the figure.

When crossing the Earth, atmospheric neutrinos can be also used to discriminate between the two MO scenarios, thanks to the matter effects acting during their propagation. Atmospheric neutrinos can thus be used by JUNO to provide a complementary measurement of neutrino MO, in a totally independent way with respect to reactor antineutrinos.

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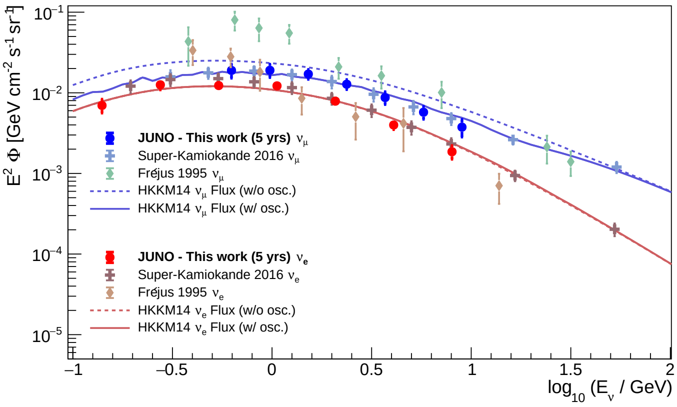


Figure 4: Atmospheric neutrino energy spectra reconstructed by JUNO [4], assuming 5 years of detector exposure. Present measurements [16] and HKKM14 [15] model predictions in the same energy range are also reported.

5. Solar neutrinos

Another natural neutrino source accessible to JUNO is the Sun's core. As a result of the nuclear fusion processes occurring in our star, ~MeV neutrinos can be detected by JUNO with unprecedented statistics, with respect to past experiments. Solar neutrinos are an important probe both to solar physics and to neutrino oscillation physics [5]. Figure 5 shows that in most scenarios, JUNO will be able to improve the current best measurements on ^{7}Be, pep, and CNO solar neutrino fluxes.

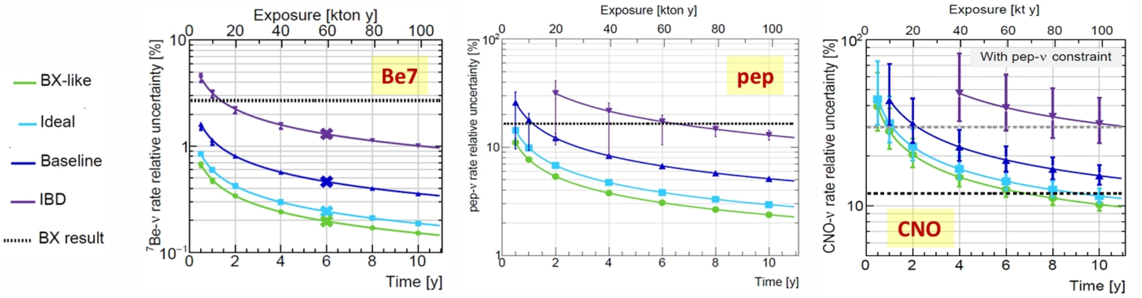
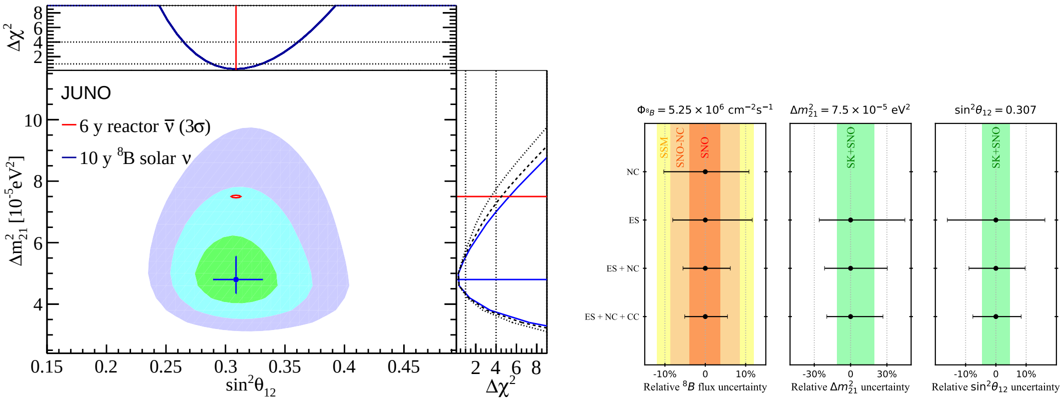


Figure 5: The relative uncertainties of ^{7}Be, pep, and CNO neutrino rates as a function of exposure [7].

Figure 6(a) shows the expected JUNO sensitivity with respect to the solar oscillation parameters, using both ^{8}B neutrinos and reactor antineutrinos. The physics potential of detecting ^{8}B solar neutrinos at JUNO in a model independent manner by using the CC, NC and ES detection channels is also studied. And the summary of relative uncertainties on the ^{8}B neutrino flux, $\sin^2\theta_{12}$ and Δm^2_{21} from the model independent approach is provided in Figure 6(b).



(a) (b)

Figure 6: (a): expected JUNO precision in the $\sin^2\theta_{12}$ and Δm^2_{21} phase space, using ^{8}B solar neutrinos and reactor antineutrinos [5]. (b): Relative uncertainties of the ^{8}B solar neutrino flux (left panel), Δm^2_{21} (middle panel), and $\sin^2\theta_{12}$ (right panel) from the model independent approach with different combinations of the data sets [6].

6. Core collapse supernova neutrinos

The large mass of the LS allows the detection of neutrinos of all flavors from a supernova explosion, with high statistics. A JUNO observation of supernovae neutrinos, in the energy range of tenths of MeV, would provide unique information about the explosion mechanism and about neutrino physics itself. Figure 7 reports the energy spectra, in terms of the visible energy, of supernova neutrinos in case of a stellar explosion inside our galaxy. Different interaction channels produce different energy distributions, representing a major improvement with respect to the SN1987A observation. Some studies show that JUNO could be sensitive also to pre–supernova neutrinos, representing a powerful tool for an early supernova alert system.

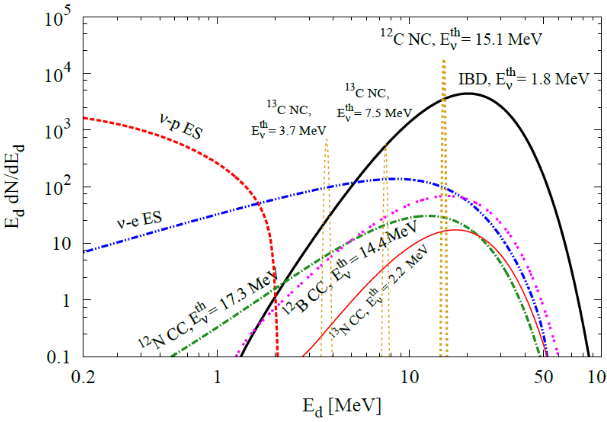
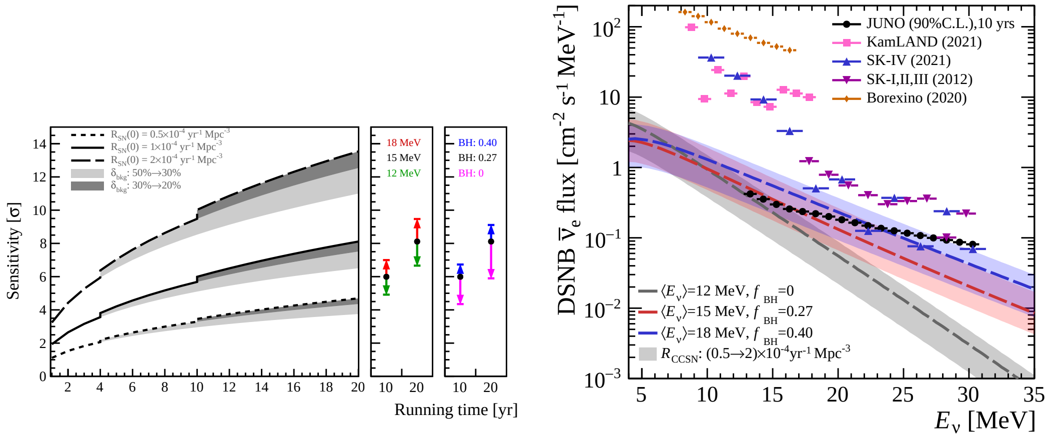


Figure 7: The visible energy (E_d) distribution of supernova neutrinos, according to different interaction channels.

7. Diffuse supernova neutrino background

JUNO can observe the supernova neutrino from the integrated signal from all past supernova explosions, namely the Diffuse Supernova Background (DSNB). The large detector mass is again the key point to address this observation, which would return important insights about the cosmological structure. In Figure 8(a) we illustrate the DSNB discovery potential at JUNO as a function of the running time. From the figure we can conclude that, for the reference DSNB signal model, JUNO can achieve the sensitivity of 3σ for around 3 years of data taking and better than 5σ after ten years. To further illustrate the model dependence of the DSNB sensitivity, we illustrate in Figure 8(b) the DSNB discovery potential as a function of model parameters for ten years of data taking. Comparing to the results of JUNO (2015) in Ref. [10], we conclude that with the latest DSNB signal prediction, more realistic background evaluation and PSD efficiency optimization, and additional TC cut, even greater discovery potential can be obtained for DSNB observation at JUNO.



(a) (b)

Figure 8: (a): DSNB discovery potential (σ) at JUNO as a function of the running time. (b): 90% confidence level upper limits on the DSNB fluxes for 18 equal neutrino energy bins from 12 to 30 MeV [9].

8. Neutrino from Earth

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 significantly improving the statistics of the existing global geoneutrino event sample [1].

9. Conclusion

JUNO is anticipated to be at the international forefront in determining neutrino mass ordering, precisely measuring oscillation parameters, and observing atmospheric neutrinos, solar neutrinos, supernova neutrinos, and geo-neutrinos. The construction of JUNO is estimated to be completed by 2024, with data taking commencing shortly thereafter.

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