PROCEEDINGS OF SCIENCE

The JUNO Experiment: Physics Prospects, Design and Status

J. P. Ochoa-Ricoux, on behalf of the JUNO collaboration[*]
University of California, Irvine
E-mail: jpochoa@uci.edu

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector that will study the reactor antineutrinos emitted by two nuclear power plants in the southeast of China at a baseline of about 53 km. With an unprecedented energy resolution of 3% at 1 MeV, JUNO will be able to determine the neutrino mass ordering at 3-4 sigma significance within six years of running. JUNO will also be able to measure three oscillation parameters to an accuracy better than 1%, and to study neutrinos from various terrestrial and extra-terrestrial sources. The experiment is currently under construction, and detector completion is expected by 2021. JUNO's physics prospects, design and status are discussed here.

The 21st international workshop on neutrinos from accelerators (NuFact2019)
August 26 - August 31, 2019
Daegu, Korea

PoS(NuFact2019)007

---

[*] Speaker.

1. JUNO Basics

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino observatory under construction in the southeast of China. As shown on the left of Fig. 1, it will be located at a distance of 53 km from two major nuclear power plants, Yangjiang and Taishan. These plants host six 2.9 GW$_{\text{th}}$ and two 4.6 GW$_{\text{th}}$ nuclear reactors, respectively, all of which are already in operation.

The JUNO detector will consist of a large ∼35 m diameter acrylic sphere containing liquid scintillator (LS) and serving as the main neutrino target. With 20 ktons of LS, representing a 20 times increase in mass over the largest LS detector currently in operation [1], JUNO will be the largest detector of this type ever built in history. The acrylic sphere will be surrounded by 18,000 20-inch and 25,000 3-inch photomultiplier tubes (PMTs) facing inwards and located in a water buffer, which together with the central LS sphere will form the so-called central detector. The latter will be immersed in an instrumented water pool serving as a muon veto detector. A schematic showing the main components of the JUNO detector is shown on the right panel of Fig. 1. As in other LS detectors, the primary detection channel will be the inverse beta-decay (IBD) reaction, $\bar{\nu}_e + p \to e^+ + n$, where the prompt signal from the positron's kinetic energy loss and annihilation precedes the neutron's capture signal on H. The coincidence between these two signals will allow to largely suppress the backgrounds when selecting IBD events.

The rest of this document presents JUNO in more detail. Its rich program in neutrino physics and astrophysics is first described in Section 2. Section 3 then discusses some of the main subsystems and their role in achieving the requirements set by the physics goals. Section 4 ends with a brief overview of the status of the project before a short summary and conclusion.

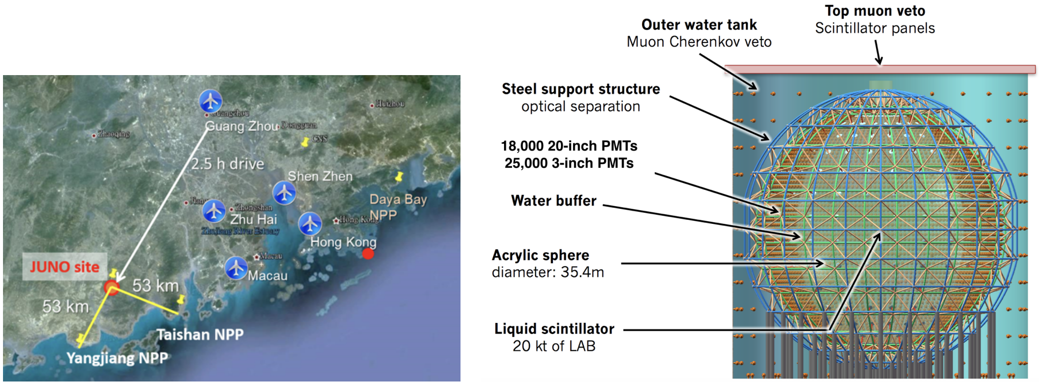

Figure 1: Left: map showing the location of the JUNO detector at a baseline of 53 km from two large nuclear power plants (NPPs) in the southeast of China. Right: schematic of some of the main parts of the JUNO detector, consisting of a 35 m diameter sphere filled with 20 ktons of liquid scintillator surrounded by around 43,000 PMTs and immersed in ultrapure water.

2. Physics Prospects

JUNO's strategic position at 53 km from the 8 nuclear reactors in the Yangjiang and Taishan nuclear power plants will enable some cutting edge measurements with reactor antineutrinos. The left panel of Fig. 2 shows the expected energy spectrum that would be observed at JUNO's location in an ideal detector with perfect energy resolution, and illustrates the small effect that the choice of mass ordering has on the subdominant "fast" oscillations (modulated by $\sin^2 2\theta_{13}$) running on top of the "slow" oscillations (modulated by $\sin^2 2\theta_{12}$). With an energy resolution of 3% at 1 MeV, JUNO will be the most precise LS detector ever constructed, and will be able to discriminate between these two scenarios to better than 3σ with 6 years of data. This will provide the community with a measurement of the mass ordering that is independent of any CP violation effects and thus complementary to what will be done by accelerator experiments [2, 3]. With its precise measurement of the oscillated spectrum, JUNO will also be able to determine $\sin^2 2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to 0.7% or better. The sub-percent precision in these parameters will have a strong impact on model building and will enable unitarity tests of the neutrino mixing matrix with unprecedented precision.

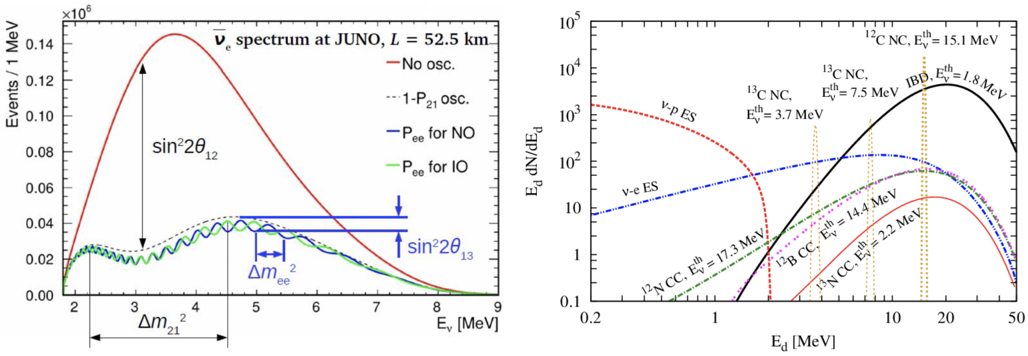

Figure 2: Left: expected energy spectra before (red) and after (blue and green) oscillations for a detector at JUNO's location with perfect energy resolution, for the normal (blue) and inverted (green) neutrino mass orderings. Right: visible energy E_d energy spectra for the main interaction channels expected at JUNO for an average core-collapse supernova at 10 kpc. The threshold neutrino energies are indicated when applicable. CC denotes charged-current, NC neutral current, and ES elastic scattering. The image is obtained from Ref. [4].

JUNO will also be able to make other measurements that are highly relevant to the neutrino physics and astrophysics communities. As illustrated on the right of Fig. 2, an average core-collapse supernova at a distance of 10 kpc would produce about 5000 IBD events and 2000 all-flavor neutrino-proton elastic scattering events, among several other channels. JUNO's large size, low threshold ($\sim$0.2 MeV) and exquisite energy resolution would provide physicists and astronomers with a wealth of information concerning the mechanisms behind supernova explosions and novel phenomena such as collective neutrino oscillations. Likewise, with an expected detection significance of 3-5σ after 10 years of data collection depending on the model considered, JUNO will either provide a leading measurement of the diffuse neutrino background from past core-collapse supernovae or one of the best constraints, in either case giving astrophysicists invaluable information on quantities like the cosmic star formation rate.

JUNO will also detect 400-500 geoneutrinos every year, which represents more than twice the total sample collected to date [6, 7, 8]. A fake data set illustrating what the prompt energy spectrum will look like in JUNO after 1 year of data is shown on the left panel of Fig. 3. Despite the large amount of reactor antineutrino background, JUNO will be able to measure the geoneutrino flux to $\sim$13% and $\sim$5% in 1 and 10 years, respectively, likely providing the world's most precise estimate of this quantity for a long time and placing important constrains on the composition and heat budget of our planet. Moreover, atmospheric neutrinos in JUNO will provide complementary information for the determination of the mass hierarchy and the octant of the θ_{23} mixing angle. JUNO's measurement of the flux of ^{7}Be and ^{8}B solar neutrinos will shed additional light on the solar metallicity problem and on the transition region between the vacuum and matter dominated neutrino oscillations. In fact, JUNO will be able to explore the $\sim 2\sigma$ tension observed in the measurements of Δm^2_{21} between reactor and solar neutrino experiments [9] with the same detector. Its 20 ktons of mass also make JUNO a competitive experiment in the search for nucleon decay. JUNO has in fact a notable advantage with the $p \rightarrow \bar{\nu} + K^+$ channel, thanks to the K^+ signal becoming visible in the LS and forming a triple coincidence with the subsequent μ^+ and e^+ signals. As shown on the right of Fig. 3, only the 40 kton version of DUNE would be able to exceed JUNO's sensitivity with this channel among all experiments under construction. JUNO will also be an excellent detector to search for other new physics scenarios such as neutrinos from dark matter, non-standard interactions, Lorentz-invariance violation, and others.

Finally, the JUNO collaboration will deploy a satellite detector called the "Taishan Antineutrino Observatory" (TAO) at a distance of about 30 m from one of the Taishan nuclear reactors. More details about the TAO detector are included in Sec. 3. With a foreseen energy resolution of $< 2\%$ at 1 MeV, TAO will make an unprecedented measurement of the shape of the reactor antineutrino spectrum, unveiling its fine structure for the first time and essentially removing any model dependence from the expected reactor antineutrino spectrum in JUNO's measurement of the mass ordering. TAO will also search for sterile neutrinos, measure the evolution of the flux and spectral shape of reactor antineutrinos with fuel composition, and decompose the reactor antineutrino spectrum into its contributions from ^{235}U and ^{239}Pu with unprecedented precision. TAO's measurements will provide a benchmark to other reactor experiments and nuclear databases for the foreseeable future.

In summary, JUNO will truly be a multipurpose observatory for neutrino physics and astrophysics. A detailed account of its rich physics prospects can be found in Ref. [5].

3. Detector Design

The physics goals place tight demands on the detector design and performance, with the most stringent requirement being the target energy resolution of 3% at 1 MeV. Achieving such a high energy resolution requires an unprecedented light level of about 1200 photoelectrons (PEs) per MeV, which is about a factor of fives times more light than what is seen in a detector like KamLAND [1]. There is no approach that can single-handedly provide all the light needed, and the problem must be attacked from different angles. These are the most critical elements in JUNO's strategy for achieving the target light level:

- Photocathode coverage: JUNO will use 20-inch PMTs as the primary light-detection devices. These will be packed as tightly as possible, resulting in a photocathode coverage of about 75% and providing a factor of $\sim$2 times more light with respect to previous LS detectors.

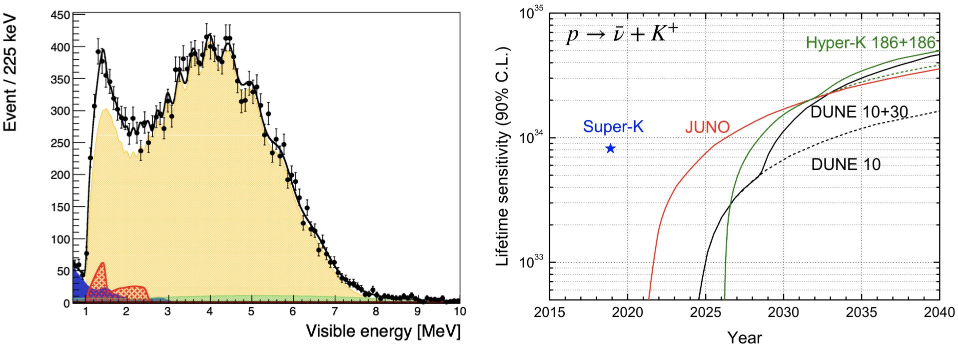

Figure 3: Left: expected prompt energy spectrum in JUNO after 1 year of data. The geoneutrino spectrum is shown in red, the reactor antineutrino background in yellow, and the additional backgrounds in other colors. The black curve represents the best fit to the full fake data set. Image obtained from Ref. [5]. Right: 90% C.L. sensitivity to the proton decay lifetime in JUNO and in other experiments under construction. The sensitivities and dates shown there are tentative and represent the best estimates known to the JUNO collaboration at the time of writing. The numbers next to the Hyper-K and DUNE experiments represent different mass scenarios in ktons.

- Scintillator light yield: JUNO will use a LS recipe inspired from the successful experience of the Daya Bay Reactor Antineutrino Experiment [10] where Linear Alkylbenzene (LAB) was used as the solvent. At 2.5 g/L however, JUNO will use more PPO scintillation fluor in order to increase the light yield, as well as 3 mg/L of Bis-MSB as the wavelength shifter. This recipe was arrived at through an optimization process carried out in one of the near detectors of Daya Bay, which was permanently decommissioned in 2017 and its central 20 ton target replaced with various recipes of JUNO LS. The final LS recipe will provide roughly 1.5 times more light than a conventional scintillator such as the one used in KamLAND.

- Scintillator transparency: given its large size, it will be very important for JUNO to control the attenuation length of its LS to > 20 m. This will be accomplished by not introducing any dopant into the LS and by exercising the Al_2O_3 column purification and vacuum distillation processes. The latter two were exhaustively tested during the aforementioned testing with one of the Daya Bay near detectors.

- High-detection efficiency PMTs: the bulk of the light produced in JUNO's central detector will be detected by a total of about 18,000 20-inch PMTs. Roughly 13,000 of these will be Microchannel Plate (MCP) PMTs, which were developed by JUNO [11] and which are being mass-produced by the North Night Vision Technology company in China. These PMTs use both transmission and reflection photocathodes in order to achieve a higher quantum efficiency compared to conventional PMTs. The other 5,000 PMTs will be R12860 from Hamamatsu, which incorporate a more efficient type of bialkali photocathode. Both of these sensors reach a detection efficiency close to 30%, which is roughly a factor of two times higher than what was achieved by conventional PMTs in previous LS experiments.

It will also be critical for JUNO's success to keep the systematic uncertainties under control. Accordingly, an aggressive calibration program with 4 complementary systems depicted in Fig. 4

has been prepared. An Automated Calibration Unit (ACU) will deploy radioactive sources along the central axis. The ACU will also deploy a fast pulse (<1 ns) UV laser with a photon intensity ranging from hundreds of keV to a few TeV of equivalent energy and with an independent intensity monitoring system achieving a precision of $< 0.3\%$ [12]. A Cable Loop System (CLS), also depicted in Fig. 4, will position the ACU sources across a vertical plane. A Guide Tube running along the outside circumference of the sphere will provide information about the locations not reached by the CLS. Finally, a Remotely Operated Vehicle (ROV) will be deployed across the full central volume. The calibration system's main goal is to keep the energy scale uncertainty below 1%.

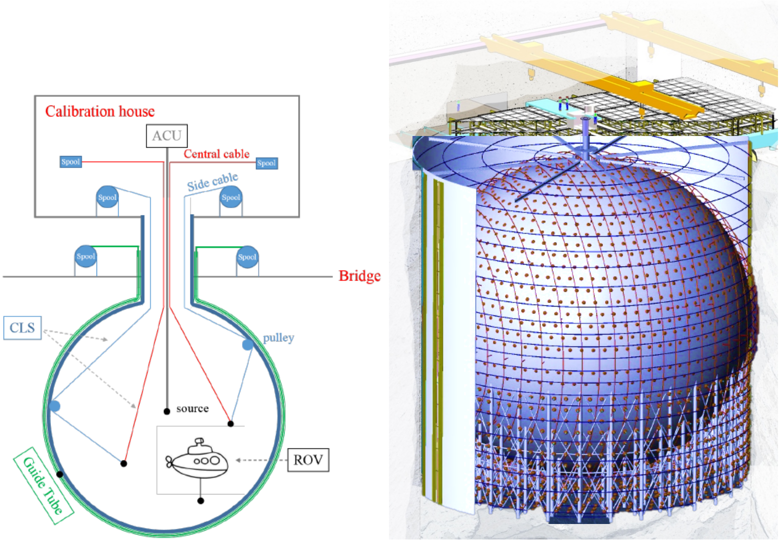

Figure 4: Left: schematic illustrating JUNO's calibration strategy of four complementary systems described in the main text. Right: schematic depicting some of the main elements of JUNO's veto system, most notably the top tracker consisting of three layers of plastic scintillators and the double coil compensating system represented as the blue and red coaxial circles.

In order to mitigate the impact of any potential residual systematics, such as non-linearities in the charge reconstruction of the 20-inch PMTs, JUNO will deploy 25,000 3-inch PMTs built by the HZC company in China in the space between the large ones. Given their small surface coverage, these small PMTs will operate primarily in photon-counting mode for events below 10 MeV and will thus constitute an independent system with different systematics with which to view all events. As such, they will provide an additional handle to cross-calibrate the energy response of the large PMTs across the full detector volume. This system will also provide other benefits, such as aiding the reconstruction of muon tracks, enhancing the supernova burst neutrino rate measurement, increasing the light level, and extending the detector's dynamic range, among others.

JUNO will also employ a large veto system to suppress backgrounds. The central detector will be immersed in a cylindrical 35 kton ultrapure water cylindrical pool with a circulation system. The water will shield the central sphere against radioactivity from the surrounding and against neutrons from cosmic-rays. Further, the pool will be instrumented with roughly 2,000 20-inch PMTs, allowing to veto cosmic-ray muons with an efficiency of at least 95%. As shown on the right of Fig. 4, the veto system will be partially covered by a top tracker consisting of 3 layers of plastic scintillators that were originally used in the target tracker of the OPERA detector [13]. There will also be an electromagnetic field shielding system consisting of large coaxial coils running along two orthogonal axes, which can be seen on Fig. 4. These coils will compensate the systematic bias that the earth's magnetic field would otherwise cause on the 20-inch PMTs down to a negligible level.

Finally, as mentioned in Sec. 2, the TAO satellite detector will be deployed in the near vicinity of one of the two 4.6 $\mathrm{GW_{th}}$ nuclear reactors in the Taishan power plant. A schematic of TAO's setup is shown on Fig. 5. TAO will be a 1.8 m diameter acrylic sphere containing Gadolinium-doped LS. The sphere will be surrounded by a copper spherical shell supporting an array of Silicon Photomultipliers (SiPMs) with 94% surface coverage, allowing to reach a light level of 4500 PEs per MeV and an energy resolution of $< 2\%$ at 1 MeV. In order to reduce the SiPM dark noise, the whole detector will be placed inside a cryostat and cooled to -50°C. The cryostat will be located in a basement with a 10 m overburden and will be further shielded with HDPE, lead and other materials. In the order of 4,000 IBD interactions are expected per day in a central 1 ton fiducial volume, with about 50% of these detected due mainly to the efficiency of the muon veto and the neutron tagging.

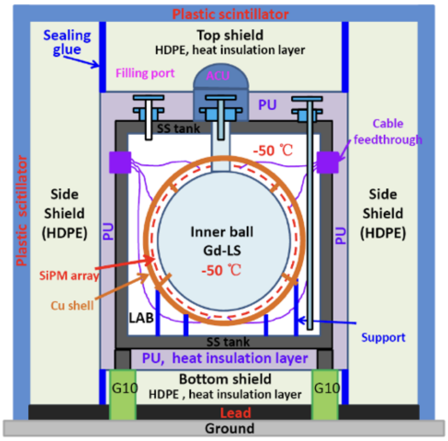

Figure 5: Schematic of the setup for the JUNO TAO satellite detector, which will be a 1 ton fiducial volume of Gadolinium-doped LS and 94% SiPM coverage operating at a temperature of -50°C. An energy resolution of 2% at 1 MeV or better is expected.

4. Status and Timeline

A rough timeline showing the main milestones of the JUNO project is shown in Fig. 6. The civil construction of the 700 m deep experimental hall is progressing well and is expected to conclude by the end of 2020. PMT mass production is well underway, with all Hamamatsu 20-inch, all HZC 3-inch PMTs, and more than 70% of the MCP 20-inch PMTs already produced. The potting of all PMTs is ongoing, and mass production of the electronics is about to be launched in early 2020. Everything is on track for detector completion by late 2021, which will only be 7 years since the conceptual design report was finished and the international collaboration established. Work on TAO is also progressing rapidly, with a ton-scale prototype already under construction. The goal is to deploy TAO around the same time the main detector comes online.

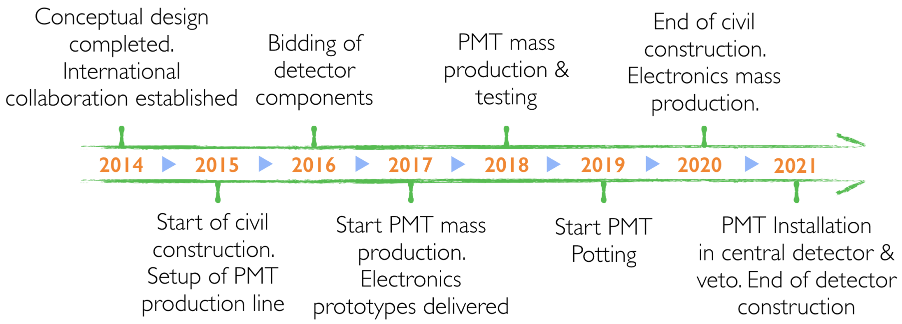

Figure 6: Rough timeline of the JUNO project with some of the major milestones.

5. Summary and Conclusions

JUNO is a multipurpose neutrino observatory under construction with a rich program in neutrino physics and astrophysics. Its goals range from performing measurements essential to our understanding of the neutrino, such as determining the neutrino mass ordering and measuring three oscillation parameters to unequaled precision, to shedding light on the makeup and workings of our Earth, Sun and Cosmos by studying the neutrinos emitted by these sources. JUNO will tackle these goals by deploying a liquid scintillator detector that is significantly larger and more precise than any other detector of this type in history. By introducing new solutions in terms of PMT technology, liquid scintillator properties and detector construction, as well as by developing some unique approaches to calibration and to the reduction of systematic uncertainties, the experiment is pushing the boundaries in liquid scintillator detection technology. Progress is well underway, and the construction of the detector is expected to be completed by 2021.

References

[1] K. Eguchi *et al.* (KamLAND), Phys. Rev. Lett. **90**, 021802 (2002).

[2] R. Acciarri *et al.* (DUNE), arXiv:1601.05471.

[3] K. Abe *et al.* (Hyper-Kamiokande), arXiv:1805.04163.

[4] J.S. Lu, Y.F. Li and S. Zhou, Phys. Rev. D **94**, 023006 (2016).

[5] F.P. An *et al.* (JUNO), J. Phys. G. **43**, 030401 (2016).

[6] T. Araki *et al.* (KamLAND), Nature **436**, 499–503 (2005).

[7] M. Agostini *et al.* (Borexino), Phys. Rev. D. **92**, 031101 (2015).

[8] M. Agostini *et al.* (Borexino), arXiv:1909.02257.

[9] M. Maltoni and A.Y. Smirnov, Eur. Phys. J. A 52:87 (2016).

[10] F.P. An *et al.* (Daya Bay), Nucl. Instr. Meth. A **811**, 133-161 (2016).

[11] Y. Chang *et al.*, Nucl. Instr. Meth. A **824**, 143-144 (2016).

[12] Y. Zhang *et al.*, J. Instrum. **14**, no. 01 (2019).

[13] N. Agafonova *et al.*, Phys. Rev. Lett. **115**, 121802 (2015).