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# Status of the JUNO experiment and its physics perspectives

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**Summary.** — The JUNO (Jiangmen Underground Neutrino Observatory), a 20 kton multi-purpose underground liquid scintillator detector, has been proposed to address outstanding issues in the neutrino sector. In the initial phase of the experimental effort, the overall concept of the structure of the detector was finalized, leading to the realization of the several components and subsystems comprised in it. Meanwhile, the experimental site was excavated and equipped to host the experiment. We are now in the final construction stage, with the detector and all its ancillary equipment being assembled underground. The main target of JUNO is the determination of the neutrino mass hierarchy, which will be accessible through the measurement of the antineutrino spectrum from two high power nuclear complexes, 53 km away from the experimental site. In this work, I briefly review the ample capabilities of the experiment for neutrino physics, which include in addition to the crucial measure of the neutrino hierarchy, the high precision determination of three oscillation parameters, as well as a vast number of potential astroparticle physics investigations. I illustrate also the main technical characteristics of JUNO, which form the basis for its ambitious physics goals.

## 1. – Introduction

In the global context of the future experimental investigations of neutrino oscillation phenomenon, the JUNO detector [1] will play a central role on two aspects: the determination of mass hierarchy and the precise measurements of the solar oscillation parameters, *i.e.*, $\Delta m^2_{21}$ , $\sin^2\theta_{12}$ , as well as the atmospheric squared mass difference $\Delta m^2_{31}$.

JUNO has been designed as a huge liquid scintillator detector, therefore exploiting a mature and well proved technology, which has already provided fundamental contributions to the neutrino studies through several implementations (Borexino [2], KamLAND [3], Daya Bay [4], Reno [5] Double Chooz [6] and SNO+ [7] being the most recent examples). It will base its measurements on the detection of the antineutrino flux coming from the cores of two nearby nuclear complexes, Yangjiang and Taishan, located at about 53 km from the experimental site.

 

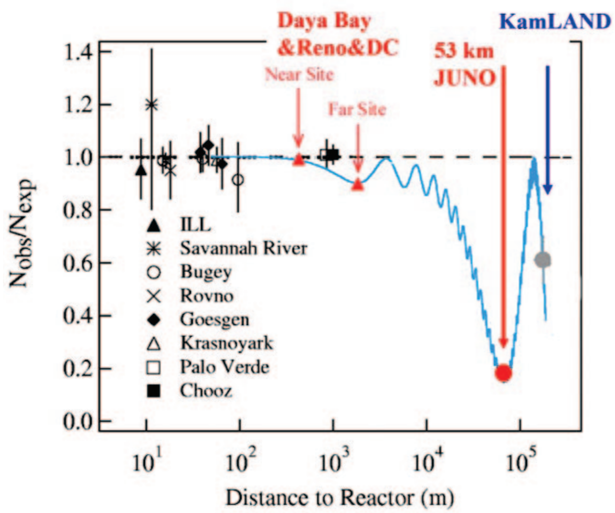


Fig. 1. – Summary of past reactors' results as ratio of observed to expected count rate, together with the predicted JUNO point.

The program will be complemented by a suite of astroparticle physics measurements which will significantly enhance the physics potential of JUNO.

Overall goals, requirements, technical features and present status of the experiment are illustrated in the following.

## 2. – Summary of characteristics and of physics goals

In fig. 1 there is the synopsis of reactors' results accumulated so far, expressed as ratio of observed over expected events, compared with the prediction from the oscillation survival probability function. On the horizontal axis the reactor-detector distance is displayed; the plot reports the well-known circumstance that at small distance the impact of the oscillation phenomenon on the detector count rate is not visible, while it starts to manifest from roughly little less than 1 km baseline. At the special distance of 53 km the count rate suppression, mainly driven by the solar oscillation parameters, is maximal, therefore creating the best condition to study the interference effect governed in turn by the atmospheric mass squared difference, which is responsible for the ripple superimposed on the count rate suppressed profile. This is, therefore, the rationality beyond the choice of the optimum site and distance between JUNO and the emitting anti-neutrino cores.

To fully exploit this optimal baseline to perform an effective and successful measurement of the mass hierarchy, the detector must be endowed with two essential characteristics: large mass to perform a high statistic measurement, and stringent energy resolution to clearly distinguish the ripple induced by the atmospheric mass squared term. The two key numbers in these respects are the total mass of 20 kton of liquid scintillator, and the energy resolution of 3% at 1 MeV, which represent, therefore, the major technical features characterizing the experiment.

In term of physics reach, such a high mass detector can tackle a plurality of mea-

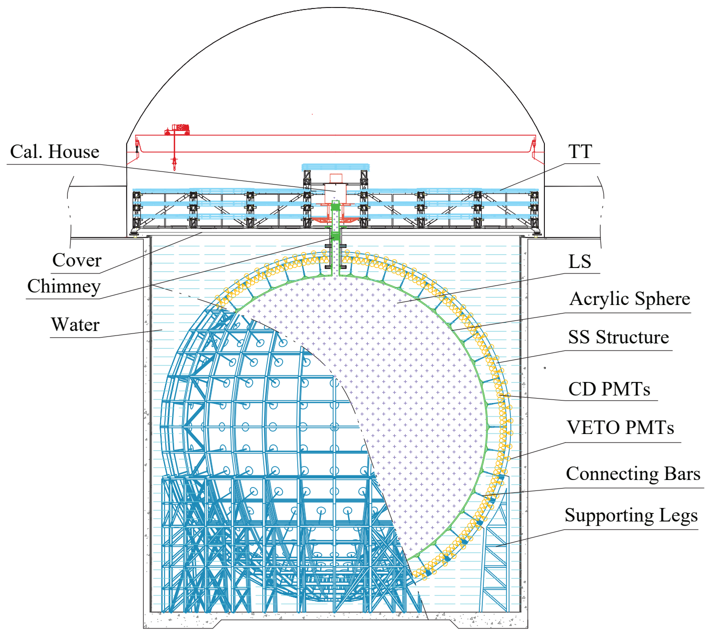


Fig. 2. – Schematic view of the JUNO configuration.

surements. Beyond mass hierarchy and precision determination of neutrino oscillation parameters, it can provide fundamental results concerning many hot topics in the astroparticle field, like supernova burst neutrinos, diffuse supernova neutrinos, solar neutrinos, atmospheric neutrinos, geo-neutrinos, sterile neutrinos, nucleon decay, indirect dark matter search, as well as a number of additional exotic searches; for details of the JUNO physics see [8] and the more recent review in [9].

## 3. – Basic features of the program: detector structure, location and collaboration

JUNO is a spherical unsegmented liquid scintillator detector that will push such a technology beyond the present limit, as far as the mass (20 kton) and the resolution (3%) are concerned. Succinctly, the detector (see fig. 2) can be described as a large spherical acrylic vessel, which will hold the scintillator volume, contained in turn in a water pool, to ensure adequate shielding against the gamma radiation and neutrons from the rock.

The vessel will be surrounded by a stainless-steel truss, which will perform the twofold task to sustain the vessel, by relieving its internal stress, and to provide the anchor support for the about 18000 20” photomultipliers observing the scintillation photons. The light detection system will comprise also an additional set of 3” PMTs, up to 25000, which will be used for calibration purpose and to cross check the performances of the main PMTs, with the scope to control and reduce the systematic effects of the measurements performed by the main 20” PMT system.

Moreover, the shielding water around the acrylic vessel will be converted into a Cherenkov detector, being instrumented with about 2000 phototubes, which will detect the muon induced Cherenkov light. Such an arrangement, together with the top tracker that will be deployed on the roof of the detector itself, will allow an efficient muon veto capability, an essential feature at the shallow depth of the experiment, *i.e.*, about 700 m.

JUNO has been approved in China at the beginning of 2013 and has been later joined by groups from all over the world. Currently the Collaboration encompasses 74 institutions from Asia, Europe and America, with more than 700 researchers, and it is still expanding.

The experiment is located in the South of China, Guangdong province, Jianmeng County, Kaiping city, at 53 km from the two sites of Yangjian and Taishan, where 6 and 2 nuclear cores are built and in operation, respectively, for a total installed power of 26.6 GW.

## 4. – How to infer the mass hierarchy

The Inverse Beta Decay Reaction a là Cowan Reines used to detect the anti-neutrino signal is the following

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

The energy deposited by the positron in the scintillator, *i.e.*, its kinetic energy plus the total 1.022 keV energy of the two annihilation gammas, reflects faithfully the energy of the incoming anti-neutrinos

$$E_{vis}\left(e^+\right) = E\left(\nu\right) - 0.8\,\mathrm{MeV}$$

$E_{vis}(e^+)$ is, thus, the individual measurement output to be analyzed for the hierarchy evaluation, which relies on the identification of the spectral distortion induced by the electron neutrino survival probability Pee.

Specifically, the effect of Pee on the measured neutrino spectrum is shown in fig. 3; the y axis is proportional to the event rate, while on the x axis the ratio L/E_$\nu$ is reported. The dashed line is the un-oscillated spectrum; the continuous black line is the spectrum distorted and suppressed as an effect of the "solar" oscillation: this large effect is the key for the very precise determination of the two "solar" mixing parameters $\Delta m^2_{21}$ and $\sin^2\theta_{12}$.

The blue and red lines superimposed on the smooth black line, instead, display the effect of the interference term driven by the atmospheric mass squared difference. The frequency of the ripple depends on $\left|\Delta m^2_{31}\right|$ (which therefore can also be determined with high accuracy from the precise "tracking" of the ripple itself), while its phase is linked to the MH, as shown by the reciprocal shift of the blue and red lines in the figure. Unraveling the phase of the ripple, hence, is the clue for the MH determination.

To this purpose, obviously, the ripples must be preserved as much as possible throughout the detection process, setting the stringent requirement on the energy resolution of being equal or better than 3%, representing by far the greatest challenge of the experiment.

Concrete $\chi^2$ calculations performed with the input parameters related to JUNO detector and site (*i.e.*, baseline 53 km, fiducial volume 20 kt, thermal reactor power 26.6

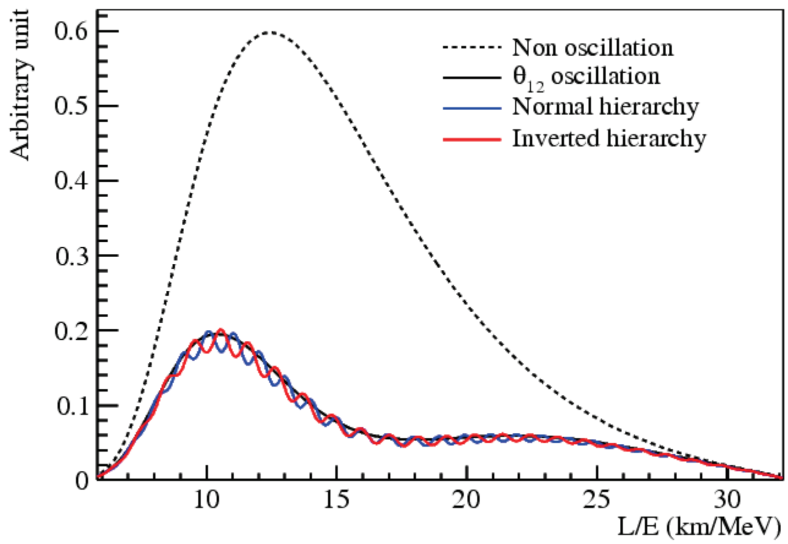


Fig. 3. – Electron neutrino survival probability on the reactor spectrum.

GW, exposure time 6 years, proton content 12%, energy resolution 3%) indicate that the statistical discrimination power of the experiment amounts to a $\Delta\chi^2$ equal to 11.3 between the true and wrong hierarchy hypothesis.

However, if systematic effects are considered, there is unavoidably a loss of discrimination power. The most important in this respect are the non-exactly equal baselines from the nuclear cores to the experiment, characterized by a spread of about 500 m, the shape uncertainty of the reactor spectrum, and the background uncertainty. All in all, these effects bring the discrimination power down to $\Delta\chi^2 = 9.0$. Therefore, JUNO has a MH 3 $\sigma$ sensitivity in 6 years of data taking [10].

Another effect highlighted is the possible impact on the MH measurement of the sharp irregularities in the original reactor spectrum discussed in [11]. To mitigate their influences, the Collaboration has decided to build a scintillator-based near detector, located close to one of the Taishan core. This Taishan Antineutrino Observatory (TAO) [12] will provide a high statistics and high resolution (about 1%) assessment of the initial reactor spectrum.

## 5. – Precision measurement of oscillation parameters

The huge effect of the survival probability on the reactor spectrum and the large amount of data that will be accumulated (JUNO plans to record 100000 events in 6 years of data taking) make it possible to measure three of the mass-mixing parameters with unprecedented sub-percent precision: the two solar parameters $\Delta m^2_{21}$ and $\sin^2\theta_{12}$, as well as the atmospheric mass splitting $\Delta m^2_{31}$.

With statistics and systematics together, the uncertainty of the measurements of these parameters is predicted to be very limited after six years of data taking, *i.e.*, 0.2%, 0.3% and 0.5% for $\Delta m^2_{31}$, $\Delta m^2_{21}$ and $\sin^2\theta_{12}$, respectively, taking also into account the correlation among them [13]. These potential results represent a dramatic ten-fold increase with respect to the current precision on the same parameters and will allow a tight test of the unitarity of the mixing matrix.

## 6. – Other physics reach

The JUNO detector is not limited to detect antineutrinos from the reactors, but also observe neutrinos/antineutrinos from terrestrial and extra-terrestrial sources, including supernova burst neutrinos, diffuse supernova neutrino background, geoneutrinos, atmospheric neutrinos, and solar neutrinos. For example, a neutrino burst from a typical core-collapse supernova at a distance of 10 kpc would lead to about 5000 inverse-beta-decay events and about 2000 all-flavor neutrino-proton elastic scattering events in JUNO, which are of crucial importance for understanding the mechanism of supernova explosion and for exploring novel phenomena such as collective neutrino oscillations. Detection of 1–2 neutrinos per year from all past core-collapse supernova explosions in the visible universe can further provide valuable information on the cosmic star-formation rate and the average core-collapse neutrino energy spectrum. Antineutrinos originating from the radioactive decay of uranium and thorium in the Earth can be detected in JUNO with a rate of roughly 400 events per year, significantly improving the statistics of existing geoneutrino event samples. Atmospheric neutrino events collected in JUNO can provide independent inputs for determining the mass ordering and the octant of the $\theta_{23}$ mixing angle.

Detection of the $^7$Be and $^8$B solar neutrino events at JUNO would shed new light on the solar metallicity problem and examine the spectral transition region between the vacuum and matter-dominated neutrino oscillations.

Finally, the JUNO detector provides sensitivity to physics searches beyond the Standard Model. As examples, the searches for proton decay via the $p \to \overline{\nu} K^+$ decay channel, neutrinos resulting from dark-matter annihilation in the Sun, violation of Lorentz invariance via the sidereal modulation of the reactor neutrino event rate, and the effects of non-standard neutrino interactions.

## 7. – JUNO construction progress and schedule

The experiment is on the edge to start data taking. The ground breaking signaling the startup of the excavation of the experimental site occurred in January 2015. After six year of intense digging and one more year to equip the laboratory underground with all the needed utilities, the installation of the detector started at the beginning of 2022.

Before that, and in parallel with the civil construction, the collaboration prepared at different construction sites all the detector components, e.g., phototubes, acrylic panels, electronics, ancillary plants and so on. This allowed to start immediately the final assembly of the detector at full steam once the site was made available.

Currently almost half of the detector has been assembled, while all the ancillary plants, including the crucial purification units for the scintillator, have been installed. This scenario is in line with the goal to ensure the completion of the detector fill and the startup of data taking before the end of 2024.

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REFERENCES


[1] JUNO Collaboration (Adam T. *et al.*), *The JUNO Conceptual Design Report*, arXiv:1508.07166 (2016).

[2] Borexino Collaboration (Alimonti G. *et al.*), *Nucl. Instrum. Methods Phys. A*, **600** (2009) 568.

[3] KamLAND Collaboration (Abe S. *et al.*), *Phys. Rev. Lett.*, **100** (2008) 221803.

[4] Daya Bay Collaboration (An F. P. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 171803.

[5] RENO Collaboration (Ahn J. K. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 191802.

[6] DOUBLE CHOOZ Collaboration (Abe S. *et al.*), *Phys. Lett. B*, **723** (2013) 66.

[7] The SNO+ Collaboration (Albanese V. *et al.*), *JINST*, **16** (2021) P08059.

[8] JUNO Collaboration (An F. *et al.*), *J. Phys. G: Nucl. Part. Phys.*, **43** (2016) 030401.

[9] JUNO Collaboration (Abusleme A. *et al.*), *Progr. Part. Nucl. Phys.*, **123** (2022) 103927.

[10] Zhang Jinnan, *JUNO Neutrino Mass Ordering Sensitivity*, *Neutrino 2022 Conference*, `https://doi.org/10.5281/zenodo.6775075`.

[11] Forero D. V. *et al.*, arXiv:1710.07378, (2017).

[12] JUNO Collaboration (Abusleme A. *et al.*), arXiv:2005.08745, (2020).

[13] JUNO Collaboration (Abusleme A. *et al.*), *Chin. Phys. C*, **46** (2022) 123001.