

Neutrino Astrophysics with JUNO

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DOI: <http://dx.doi.org/10.3204/DESY-PROC-2016-05/20>

The Jiangmen Underground Neutrino Observatory will aim for the determination of the neutrino mass hierarchy with a medium baseline reactor $\bar{\nu}_e$ oscillation experiment. With its 20 kt liquid scintillator detector, it will also be sensitive to astrophysical low-energy neutrinos. In case of a typical galactic core-collapse supernova, ~ 5000 neutrino interactions will be detected via the inverse beta decay alone. Moreover, a 3σ evidence for the diffuse supernova neutrino background seems within reach after ten years of measurement. The performance of the experiment's solar neutrino program will decisively depend on the achieved radiopurity and cosmogenic background rejection efficiency.

As underlined by the ongoing measurements of solar neutrinos by BOREXINO [1], the search for the *diffuse supernova neutrino background* (DSNB) with SUPER-KAMIOKANDE [2] or the general waiting for the next core-collapse *supernova* (SN) after SN1987A [3] that provides a neutrino signal, neutrino astrophysics is a vivid, interdisciplinary field in neutrino physics. Measurements of astrophysical low-energy neutrinos by finished and still running experiments already provided valuable information on the light neutral leptons and their extraterrestrial sources. However, the answering of currently outstanding questions concerning SN neutrinos, the DSNB or ν_e 's from the Sun requires neutrino observatories of the next generation. The *Jiangmen Underground Neutrino Observatory* (JUNO) [4, 5], although under construction for a different primary purpose, prepares to aid with their answering.

A brief overview of the main goal of JUNO and the design of its 20 kt liquid scintillator detector is subject of Section 1. The use of the detector to collect a high-statistics neutrino sample with energy, time and partial flavor information in case of a galactic core-collapse SN is topic of Section 2. Besides the opportunity to learn more about the properties of neutrinos, such a sample of SN- ν events will be a critical test for models of stellar collapses. The estimated performance of JUNO to detect the predicted flux of low-energy neutrinos from past core-collapse SNe, the DSNB, is covered in Section 3. Finally, Section 4 outlines a possible solar neutrino program of JUNO.

1 The JUNO project

The JUNO project is an international undertaking centered on the construction of a 20 kt liquid scintillator neutrino detector in the south of China. Its primary goal is the determination of the neutrino *mass hierarchy* (MH). This means to answer the question whether the third neutrino mass eigenvalue m_3 is larger (Δm_{31}^2 and $\Delta m_{32}^2 > 0$; $\Delta m_{ij}^2 = m_i^2 - m_j^2$) or smaller (Δm_{31}^2 and

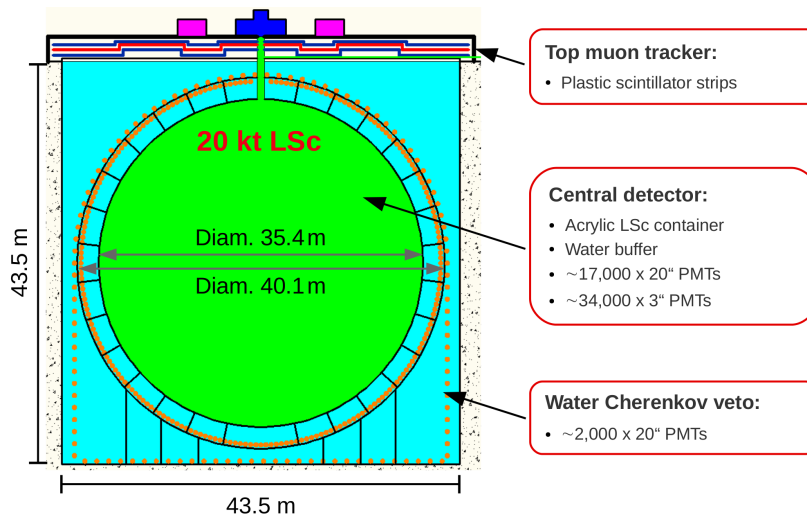


Figure 1: Design of the 20 kt liquid scintillator detector of JUNO. For details see [4, 5].

$\Delta m_{32}^2 < 0$) than the other two mass eigenvalues m_1 and m_2 , which are known to be separated by $\Delta m_{21}^2 > 0$. To do so, a precise measurement of the hierarchy-dependent oscillatory fine structure in the energy-dependent survival probability of reactor $\bar{\nu}_e$'s will be performed. Two nuclear reactor complexes with about 53 km distance to the detector will provide the $\bar{\nu}_e$ flux of interest. The measurement procedure requires an energy resolution of 3% at 1 MeV in order to discriminate the different hierarchy signatures (for details see [4]).

As usual for hydrocarbon-based detectors, the primary detection channel for the $\bar{\nu}_e$'s is the *inverse beta decay* (IBD) on free protons: $\bar{\nu}_e + p \rightarrow e^+ + n$. The signature from the coincidence of the prompt positron annihilation (on the order of nanoseconds) and the delayed neutron capture (after about 200 μ s) allows for an efficient background rejection. With about 100 k IBD events, the expected median MH sensitivity of JUNO alone is around 3σ . This corresponds to six years of running with ten reactor cores and a total thermal reactor power of 36 GW.¹ Taking into account external information with 1.5-1% precision on the modulus of the atmospheric mass splitting $\Delta m_{\mu\mu}^2$ (a linear combination of Δm_{21}^2 , Δm_{31}^2 and Δm_{32}^2), the median sensitivity reaches 3.7-4.4 σ [4]. Additionally, the high-statistics reactor $\bar{\nu}_e$ measurement will reduce the uncertainty on the underlying (effective) flavor oscillation parameters $\sin^2 \theta_{12}$, Δm_{21}^2 and $|\Delta m_{ee}^2|$ to sub-percent level [4].

The site for the new neutrino observatory is located close to *Kaiping*, about 150 km west of *Hong Kong* and about 120 km south-west from *Guangzhou*. With JUNO being a funded project – and aiming for a start of data taking by 2020 – the first construction works for the underground laboratory started at the beginning of 2015. It will have a rock overburden of about 700 m (~ 1800 m w.e.), leaving an atmospheric muon event rate on the order of 3 s^{-1} in the detector.

Both the unprecedented liquid scintillator mass of 20 kt and the design requirements to reach the energy resolution goal will make JUNO advance the liquid scintillator technology beyond the

¹The total thermal reactor power at the start of data taking by 2020 will be 26.6 GW.

current state of the art. In the existing detector design, which is illustrated in Figure 1, the core component of the detector is the LAB-based liquid scintillator as designated neutrino target. It is contained in an acrylic sphere of 35.4 m inner diameter. Surrounded by ultra-pure water, the sphere is held in place by a stainless-steel latticed shell with 40.1 m inner diameter. The shell also holds the inward-facing photosensors. About 17,000 *photomultiplier tubes* (PMTs) with 20" diameter constitute the base system for the calorimetric energy measurement. Placed between the large PMTs, around 34,000 additional PMTs with 3" diameter provide a second calorimetry system and better timing for event position reconstruction. To reach the required energy resolution in terms of photon–electron statistics, the design goal for the *photoelectron* (pe) yield is about 1200 pe/MeV after non-uniformity corrections. This implies certain requirements for the PMT photocathode coverage ($\geq 75\%$), the maximum PMT quantum efficiency ($\geq 35\%$) and the liquid scintillator properties (attenuation length ≥ 20 m at 430 nm wavelength). Moreover, the energy resolution is also connected to a precise calibration of the energy scale, which must be ensured in the presence of dark noise from the PMTs and the electronics as well as finite vertex and PMT charge resolutions.

The described detector construct is submerged and anchored in a cylindrical water pool of 43.5 m height and diameter. Equipped with about 2,000 PMTs of 20" diameter, the ultra-pure water in the pool acts as Cherenkov-based atmospheric muon veto and as shielding against external radiation. A tracker composed of plastic scintillator strips for downward-going muons partially covers the pool on the top.

2 Neutrinos from a core-collapse supernova burst

The death of a massive star in a core-collapse SN is among the most violent phenomena in the visible universe. Most of the energy released in a SN burst, about 3×10^{53} erg, is carried away by myriads of neutrinos and antineutrinos of all flavors. They are produced at the origin of the final explosion, making the weakly interacting particles valuable messengers for information directly from the star's collapsing interior. The information they provide is complementary to the one from the optical SN signal and can be gathered even if the SN's visual appearance is obscured by galactic dust.

A flavor, time and energy resolved neutrino burst signal from a core-collapse SN would allow to test our current understanding of the dynamics inside a dying star (e.g., see [6]). In particular, theoretical expectations regarding different stages of the cosmic event, like the ν_e *burst*, the *accretion phase* and the *cooling phase*, or effects from (collective) neutrino flavor oscillations could be probed. Both gravitational wave data and an abruptly ending SN- ν signal could even indicate the formation of a black hole. As a consequence, the broad insights into core-collapse physics offered by SN- ν 's sets the collection of a high-statistics sample of these promising witnesses among the top priorities of neutrino astrophysics. Once operational, JUNO will stand by for the next of only 1-3 expected low-energy neutrino bursts per century from a galactic core-collapse SN.

Real-time detection of SN- ν 's with the liquid scintillator detector of JUNO will benefit from the very good energy resolution, the large target mass and partial flavor information. As listed in Table 10 of [4] for different SN- ν mean energies and a galactic core-collapse SN at a typical distance of 10 kpc,² between 4300 and 5700 SN- $\bar{\nu}_e$ events are expected in the IBD channel alone during the about 10 s lasting SN signal. However, the hydrocarbon-based target material offers

²Numbers are without flavor conversion effects.

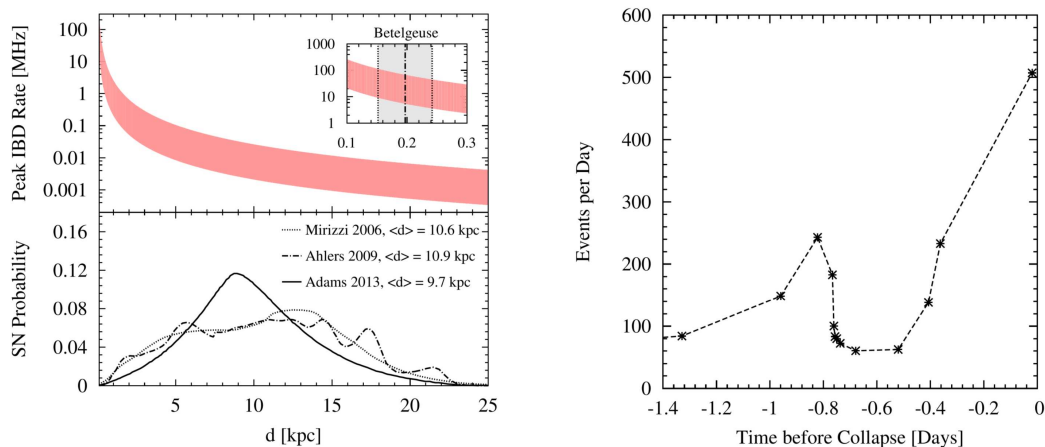


Figure 2: Left: Core-collapse SN probability (lower panel) based on different models and peak IBD event rate (upper panel) as a function of the distance to the SN. The inlay in the upper panel shows the expected peak IBD event rate specifically for *Betelgeuse* at 0.197 ± 0.045 kpc [8]. Right: Expected neutrino event rate in JUNO from the silicon burning stage of a massive $20 M_{\odot}$ star at 0.2 kpc distance as a function of the time before the SN explosion. The drop in the event rate after the silicon burned out gives information on the progenitor mass. Figures from [4].

additional opportunities for time-resolved detections of neutrino interactions: *Charged current* (CC) reactions on carbon nuclei, $\bar{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}$ and $\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$, probe the $\bar{\nu}_e$ flux, but additionally give access to the ν_e component. One *neutral current* (NC) interaction on carbon, $\nu(\bar{\nu}) + {}^{12}\text{C} \rightarrow \nu(\bar{\nu}) + {}^{12}\text{C}^*$, and elastic scattering on electrons are sensitive to the total neutrino flux. Even more NC events are expected to occur via elastic neutrino scattering on free protons [7]. These interactions are detectable in liquid scintillator, but require that the heavily quenched visible energy from the proton recoil is above the low-energy limit at about 200 keV, which is imposed by background from intrinsic ${}^{14}\text{C}$ decays. With 600 to 2000 expected events above this threshold, the elastic neutrino–proton scattering channel would have the second highest statistics.

JUNO will be sensitive mostly to galactic SNe. The large number of events in JUNO at such occasions provides detailed neutrino “light curve” spectra and allows to test core-collapse SN models. Due to the high event rate during the 10 s SN- ν signal, background is no serious concern. For SNe at larger distances R , the number of neutrino events decreases as $1/R^2$. As an example, only about 200 events are expected from the 50 kpc distant *Large Magellanic Cloud* where SN 1987A [3] exploded and produced the first and last measured SN- ν signal. The objective not to miss the next galactic core-collapse SN also means that the JUNO detector must not be “blinded” by neutrinos in case of a nearby incident. A particular close SN candidate is the around 0.197 kpc distant red supergiant *Betelgeuse* [8] with about 18 solar masses. If it becomes a SN, the expected peak IBD rate in JUNO reaches about 10^8 s^{-1} (see upper panel of Figure 2 left) for some tens of milliseconds roughly during the first 200 ms of the SN signal. This sets additional constrains for the design of the data acquisition.

Due to the capabilities of JUNO, the detector will surely become part of the *Supernova Early Warning System* (SNEWS) [9]. For close progenitors, e.g., *Betelgeuse*, the ultimate pre-

warning system is the detection of neutrinos from the short silicon-burning stage briefly before the explosion, as illustrated in Figure 2 right. Besides the use of such pre-SN neutrinos to verify stellar models, the sudden drop of the event rate when the silicon in the star burned out contains information on the progenitor mass.

Neutrinos from SNe can be used to locate the cosmic incident even if the visual appearance is obscured. One method relies on the study of the displacement between the IBD vertices from the prompt positron signal and the delayed neutron capture, which is statistically related to the original neutrino direction [10]. Assuming 5000 IBD events in JUNO, it is expected that the sky coordinates of the galactic core-collapse SN can be measured with about 9° uncertainty, perhaps even better.

3 Neutrinos from the diffuse supernova neutrino background

The DSNB is the flux of neutrinos from past core-collapse SNe in the visible universe. Its measurement would provide valuable information on the star formation rate, the average core-collapse neutrino spectrum and the rate of failed SNe. So far, only upper limits on the flux could be set by SUPER-KAMIOKANDE [2].

The DSNB sensitivity forecast for JUNO adopted the practice for the physics study of the *Low Energy Neutrino Astronomy* (LENA) project [11]. It relies on a parametric representation of the isotropic DSNB flux, where important ingredients are the SN rate as a function of red shift and the neutrino flux spectrum (for details see [4]). The latter was taken to be a Maxwell-Boltzmann distribution, which introduced the average neutrino energy as parameter with considered values between 12 and 21 MeV. Taking flavor conversion effects into account, it is assumed that the total energy release in neutrinos per core-collapse SN is distributed evenly between neutrinos and antineutrinos of all flavors. Therefore, the IBD channel is used to measure the $\bar{\nu}_e$ component of the DSNB flux with the liquid scintillator detector of JUNO.

About 0.9 to 1.7 DSNB events per year are expected for JUNO in the analysis energy window from 11 to 30 MeV after all cuts, depending on the average $\bar{\nu}_e$ energy. Below the lower limit of the visible energy window, the strong, irreducible background from reactor $\bar{\nu}_e$ dominates. At energies above the upper limit, CC interactions of atmospheric $\bar{\nu}_e$ are the dominant background. Moreover, the NC interactions of atmospheric neutrinos above 8 MeV can fake an IBD signal: If a neutron knocked-out from carbon scatters on protons, a prompt signal signature is created. The neutron capture subsequently makes the delayed signal. However, *pulse shape discrimination* (PSD) for the light³ signal of the prompt event and the search for a disexcitation of a left-behind ^{11}C nucleus can help to reduce this challenging background inside the energy range of interest. In fact, the PSD performance is decisive for the sensitivity to the DSNB. As for LENA, a NC background rejection efficiency of 98.9% at the cost of 50% of the signal is assumed. Due to the PSD and the energy cuts, backgrounds from cosmogenic isotopes and fast neutrons can be neglected. Table 13 in [4] lists expected DSNB detection significances after ten years of measurement with JUNO for different assumptions about the average neutrino energy and systematic background uncertainties. For favored DSNB parameters, a 3σ evidence for the DSNB signal seems within reach. As shown in Figure 3, a significant improvement of the

³The observed scintillation pulse shape of the liquid scintillator is different for traversing positrons and protons.

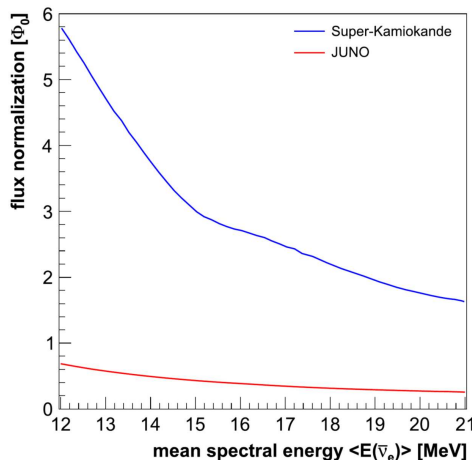


Figure 3: Predicted DSNB exclusion contour (90% C.L.; lower red line) if JUNO finds no DSNB signal above background after ten years of measurement. The upper limit for the DSNB flux normalization Φ_0 (for details see [4]) is given as a function of the mean energy of the SN- $\bar{\nu}_e$ spectrum $\langle E_{\bar{\nu}_e} \rangle$. For comparison, the upper limits from the SUPER-KAMIOKANDE results (upper blue line) presented in [2] are also shown. Figure from [4].

current upper limits on the DSNB flux from SUPER-KAMIOKANDE [2] can be made if there is no positive detection after ten years.⁴

4 Neutrinos from the Sun

Measurements of ν_e from the Sun, e.g., with SNO or BOREXINO [1], gave valuable insights into the energy release processes in our home star. Moreover, they enabled the study of neutrino flavor changes in surroundings with varying matter density, allowing first tests of predictions from the MSW effect (e.g., see Figure 5 in [13]). Yet there are still open issues: The solar metallicity, i.e., the composition of the Sun in terms of elements heavier than helium, is not conclusively determined. None of current solar models with different metallicities and opacities is in full agreement with neutrino measurements and observations from helioseismology. Moreover, looking at solar ν_e oscillations, the shape of the survival probability $P_{ee}(E_\nu)$ in the transition from the matter-dominated region at higher energies to the vacuum-dominated region at lower energies is not yet fixed. Especially the transition region around 3 MeV is sensitive to effects that can make P_{ee} deviate from the MSW *large mixing angle* (LMA) prediction.

Solar- ν measurements with the liquid scintillator detector of JUNO will be performed via elastic neutrino–electron-scattering as primary detection channel. They will benefit from the very good energy resolution of the detector and the large target mass. Table 1 lists the expected solar neutrino signal rates. However, for solar neutrino observations, the experiment needs

⁴The GADZOOKS! upgrade [12] of the water Cherenkov detector SUPER-KAMIOKANDE plans to dissolve the neutron absorber gadolinium in the 22.5 kt fiducial target mass. It is expected to increase the efficiency to tag the final state IBD neutron to $\sim 80\%$, allowing to detect 3 to 5 DSNB $\bar{\nu}_e$ events per year. For JUNO, this makes GADZOOKS! a direct competitor in the quest for the first measurement of the DSNB.

| Neutrino flux | Signal rate (counts / day / kton) |
|-------------------------------------------------------------------|-----------------------------------|
| pp ν | 1378 |
| ${}^7\text{Be}$ - ν | 517 |
| pep ν | 28 |
| ${}^8\text{B}$ - ν | 4.5 |
| ${}^{13}\text{N}$ / ${}^{15}\text{O}$ / ${}^{17}\text{F}$ - ν | 7.5 / 5.4 / 0.1 |

Table 1: Expected solar neutrino signal rates at JUNO. Data cited from [4].

to deal with radiopurity requirements that are more strict than for the MH measurement. Two scenarios for low-energy solar neutrino detection, named *baseline* and *ideal*, are currently assumed. They are summarized in Table 14 of [4]: The *baseline* case corresponds approximately to the KAMLAND solar phase purity level, yields a signal-to-background ratio of about 1:3 and makes the solar ${}^7\text{Be}$ neutrino branch accessible. In the *ideal* case, which assumes the BOREXINO phase-I purity level before 2010, the expected signal-to-background ratio is about 2:1, probably giving a solar ${}^7\text{Be}$ neutrino signal rate about three times larger than the total of all backgrounds.⁵

Besides the achievement of high radiopurity, an efficient rejection of cosmogenic background from ${}^{11}\text{C}$ and ${}^{10}\text{C}$ decays is another important task. With the experiment's overburden of ~ 700 m, about 1860 and 35 counts per day and kton are expected, respectively.

The focus of JUNO concerning solar neutrinos would be measurements of the ${}^7\text{Be}$ - ν and ${}^8\text{B}$ - ν fluxes. Together, the outcomes can help to break solar model ambiguities that cannot be resolved alone with results for neutrino fluxes from the CNO cycle in the Sun (see Figure 42 and Figure 43 in [4]). Moreover, a high-statistics measurement of the low-energy part of the ${}^8\text{B}$ - ν spectrum around 3 MeV will probe the P_{ee} transition region, allowing the search for deviations from the MSW-LMA prediction.

Conclusions

JUNO aims to determine the neutrino MH by precisely measuring the oscillatory fine structure in the survival probability of $\bar{\nu}_e$'s from nuclear reactors at a baseline length of 53 km. Once data taking begins around 2020, the neutrino observatory will feature a 20 kt liquid scintillator detector of unprecedented size and with a very good energy resolution. In case of a galactic core-collapse SN at the benchmark distance of 10 kpc, about 5000 IBD events with energy, time and partial flavor information will allow to test SN models. Concerning the DSNB, a 3σ evidence seems within reach after 10 years of measurement. If no positive DSNB signal is found, the current upper DSNB flux limits will be significantly improved. A solar neutrino program of JUNO will decisively depend on the achieved radiopurity and cosmogenic background rejection efficiency. The focus will likely be on ${}^7\text{Be}$ - ν and ${}^8\text{B}$ - ν measurements, which can help to shed light on the solar metallicity / opacity problem and on the transition region of the solar ν_e survival probability.

⁵JUNO will profit from BOREXINO expertise in terms of radiopurity.

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