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Physics potential with astrophysical neutrinos in JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a medium-baseline reactor neutrino experiment under construction in China. It will be the largest ever built liquid scintillator detector for neutrino physics. It will be sensitive to various astrophysical neutrino sources, including solar neutrinos, the diffuse supernova neutrino background, pre-supernova neutrinos and the all-flavor neutrino flux from a Galactic core-collapse supernova (CCSN) with high statistics. For maximizing the physics reach of JUNO as a neutrino telescope, two trigger systems will operate to search for a transient astrophysical signal in real time: a dedicated multi-messenger trigger system and a Prompt CCSN monitor, the latter embedded in the global trigger system. This talk will report the expected performance of JUNO for the detection of the different neutrino fluxes from the mentioned sources, describing its dedicated trigger schemes and highlighting the unique contributions it will bring to the understanding of the various astrophysical phenomena.

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1. The JUNO experiment

JUNO is a medium baseline reactor neutrino experiment, located 700 m underground [1]. It measures the electron antineutrino flux from 8 reactor cores dispatched in two nuclear power plants at 53 km distance. JUNO is the largest ever built liquid scintillator detector and has an impressive PMT coverage (78%), with more than 40k PMTs, making it a particular experiment. A schematic view of the instrument is given in Fig. 1. The central detector of JUNO consists of an acrylic sphere filled with 20 kton of liquid scintillator (LS), which will measure the light induced by the interaction of particles with the LS with two systems: 17612 20 inch PMTs and 25600 3 inch PMTs. Surrounding the central detector, there is a water pool which will act as a Cherenkov detector for vetoing atmospheric muons. In addition, on top of the detector three plastic scintillator layers will be used to sample muons, and evaluate their reconstruction performance as well as their contamination in the central detector.

The main physics goal of JUNO is determining the neutrino mass ordering (NMO) above the three sigma level after six years of data taking. For this, one needs high event statistics, very good energy resolution (of the order of 3% at 1 MeV) and a low uncertainty on the energy scale of the neutrino flux (below 1%). JUNO can fulfill these requirements thanks to its large volume, high light yield and transparency of the liquid scintillator, high PMT coverage and efficiency, the double calorimetry system, and four complementary calibration subsystems. In fact, JUNO will have a larger photon collection efficiency and better energy resolution than any previous existing experiment of that kind.

Reactor electron antineutrinos are observed through their interaction with protons via Inverse Beta Decay (IBD). This gives a very clear signature: a prompt plus delayed signal coincidence which appears in the few-MeV energy range. The prompt signal is given by the positron kinetic energy and its annihilation into two γ's, while the delayed signal appear when the product neutron thermalises and is captured in hydrogen and carbon atoms in the LS. Apart from reactor antineutrinos, JUNO will be able to measure the neutrino flux from other natural sources in a broad band of energy and flux, including solar and supernova neutrinos. This makes JUNO physics program very rich. The following sections will describe the JUNO potential to the mentioned astrophysical sources.

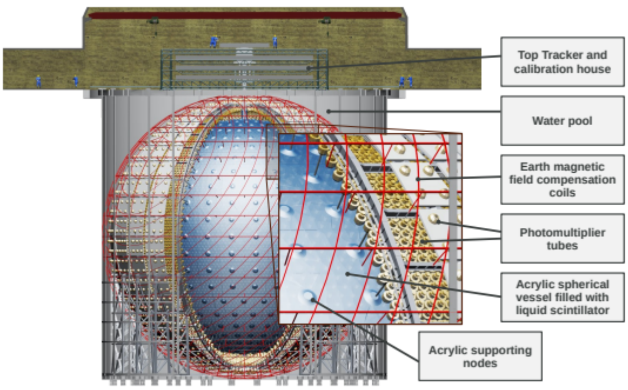

Figure 1: Schematic view of the JUNO detector.

2. Solar neutrinos in JUNO

In the of context of solar neutrinos, the main detection channel are electron neutrino elastic scatterings (ES). This means that the analysis deals with single events, were different backgrounds present high rates. Different searches can be performed aiming at the detection of the different fluxes related to the different processes in the Sun, including: pp, pep, CNO, ^{7}Be and ^{8}B neutrinos. We will divide them in two separate energy regimes in the following sub-sections.

2.1 High-energy (>2 MeV) ^{8}B solar neutrinos

In the highest energy regime (2-10 MeV), there is the ^{8}B flux that JUNO will also try to measure. The results of the most recent ^{8}B analyses are reported in [3, 4]. Fig. 2 shows the reconstructed ^{8}B spectrum after event selection on top of the different backgrounds. With JUNO, a simultaneous determination of Δm^2_{21} and $\sin^2\theta_{12}$ with both solar and reactor neutrino data is possible. A direct comparison of oscillation parameters from the solar neutrino and reactor antineutrino oscillations is an unique probe of new physics beyond the Standard Model of particle physics.

The latest analysis, includes for the first time neutrino interactions with carbon nuclei on top of the ES channel, and lowers the energy threshold down to 2 MeV. Including the charged (CC) and neutral (NC) current interactions on ^{13}C allows to have a model independent measurement of the 8B flux and the solar oscillation parameters, adding a unique contribution to the global solar neutrino program thanks to its high precision measurement achieved with its high statistics. The CC channel can be identified with its characteristic coincidence signature: the prompt signal comes from the energy deposited by the outgoing electron, and the delayed signal from the β-decay of the ^{13}N product. The NC channel is selected with a energy cut, as its typical signature is a mono-energetic γ. In this work, the day-night asymmetry, which is caused by the MSW effect inducing the ν_e regeneration on the Earth, is used to further constrain the oscillation parameters, as its magnitude strongly depends on the value of Δm^2_{21}. When combining thee channels with the ν_e-ES, and fitting simultaneously the ^{8}B flux and the solar oscillation parameters in a model independent approach, they can be measured respectively with a precision of $\pm 5\%$, $^{+9\%}_{-8\%}$, and $^{+25\%}_{-17\%}$.

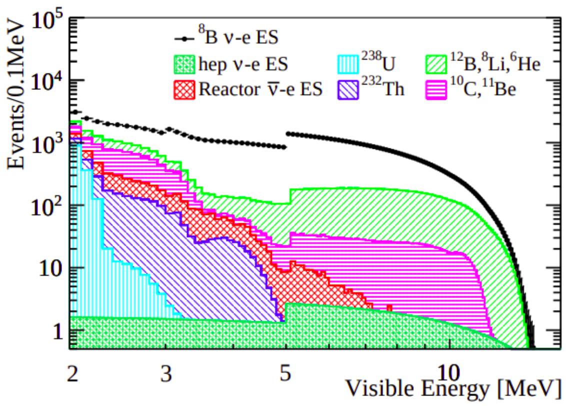

Figure 2: Expected signal and background spectra in ten years of data taking, with all selection cuts and muon veto methods applied. Figure extracted from [3].

2.2 Intermediate and low energy (<2 MeV): the pep, CNO and 7Be neutrinos

JUNO can also benefit from the large statistics and exquisite energy resolution to study intermediate and low energy solar neutrinos (<2 MeV), this means measuring the pep, ^{7}Be and CNO fluxes. For this observation, one needs to carefully evaluate the different backgrounds. First, the internal level of radioactivity is crucial. The strategy to control internal background due to radioactivity is described in detail in [5]. In the latest analysis ([6]), four different radioactivity scenarios are considered: the level required for the reactor (IBD) oscillation analysis, the baseline radioactivity level estimated for JUNO, an ideal radiopurity level, and finally the level achieved by Borexino experiment during its last data taking phase.

The main external background in JUNO is the γ radioactivity of the materials that surround the scintillator (PMTs, SS structure, and acrylic vessel). In particular, radioactive isotopes in the PMT glass that produce a signal in the typical energy range of 1–3 MeV. This contribution can be easily reduced by applying a fiducial volume cut, as the signal originates close to the border of the detector. Finally, cosmogenic isotopes are created by the spallation of cosmic muons on carbon atoms inside the liquid scintillator are considered. This background in dominated by the ^{11}C isotope and can be reduced using the so-called "Triple-Fold-Coincidence" (TFC) algorithm. Indeed, the spallation reaction by the parent muon is followed by a cosmogenic decay and a neutron capture, which gives a characteristic signature. This is exploited by using two separate data sets to have an accurate fit for the ^{11}C background contribution: one enriched with ^{1}1C and the second where it is subtracted.

Finally, solar spectroscopy is used to further discriminate between the different radioactive isotopes against the solar neutrinos, using their characteristic energy spectral shapes. The results in Fig. 3 show that JUNO will be able to improve Borexino results in 1-2 years for the ^{7}Be and pep measurements. The detailed analysis can be found in [6].

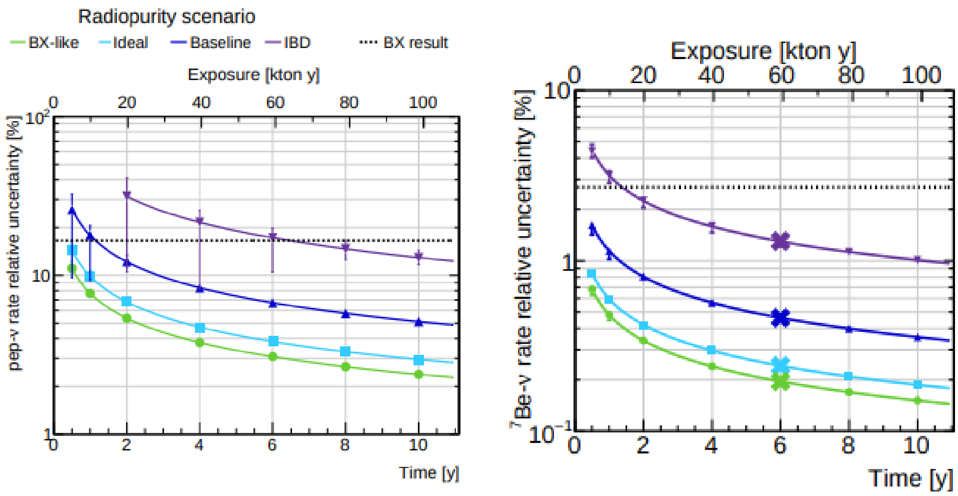

Figure 3: Relative uncertainties on the measurement of the *pep* (left) and ^{7}Be neutrino rate (right) as a function of exposure. The results for the four radiopurity scenarios are shown respectively in different colors. The best result by Borexino (17%) is indicated by the black dotted line for comparison. Fig. taken from [6].

3. The diffuse supernova neutrino background

The superposition of the neutrino signals from all past supernova explosions yields the so called diffuse supernova neutrino background (DSNB). It is a guaranteed steady flux of astrophysical neutrinos which has not been observed yet. Its discovery will bring relevant knowledge on astrophysics and cosmology, such as the cosmic star formation rates or the fraction of failed supernova with black-hole formation in the Universe, holding as well as information on the average supernova neutrino spectrum. Its detection in JUNO will be made via IBD interactions. The main backgrounds come from neutral current atmospheric neutrino interactions and fast neutrons produced by non-tagged cosmic muons. A selection using a cut on the energy range of interest [12,35] MeV, allows to remove fast neutrons at high energies, as well as reactor neutrinos and radioactive isotopes at low energies. A fiducial volume cut is also proven to be efficient in the rejection of fast neutrons. Finally, a dedicated pulse shape discrimination technique allows to reduce the atmospheric NC background contribution. As it was the case in section 2.2, the signature of the NC atmospheric background with ^{11}C are three-fold coincidences (TFC), which typically consist of a prompt signal of the fast neutron recoil, a delayed signal of neutron capture on hydrogen, and an additional signal given by the β-decay of the unstable ^{11}C. Therefore, a TFC cut is additionally applied to further increase the background rejection efficiency. After this selection (~75% signal efficiency), the expected signal rate (4-7 events/day) is at the same level as the remaining background (~5 events per day). The latest results of the analysis show that JUNO can reach a 3σ discovery potential to the DSNB signal after three years of data taking when the reference model is considered and assuming a background uncertainty of 50% [7]. As shown in Fig. 4, JUNO will be key to discriminate between the different DSNB models, and will be able to set stronger constraints than the current limits by Super-Kamiokande (SK), and go down to lower energies.

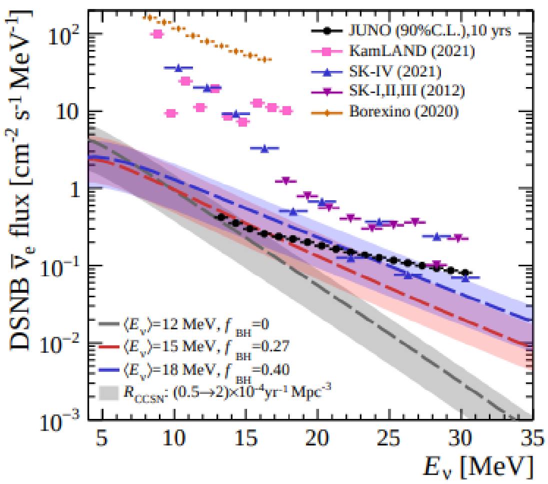

Figure 4: JUNO 90% confidence level upper limits on the DSNB fluxes for 18 equal neutrino energy bins in the range [12,30] MeV. The grey, red and blue bands with dashed lines show the DSNB flux predictions for different model parameters, with its corresponding uncertainties. JUNO sensitivity is compared to the current limits by Kamland, Borexino and SK experiments. Fig. extracted from [7].

4. Core-collapse supernova neutrinos

In contrast to solar neutrinos and the DSNB flux, a Galactic core-collapse supernova (CCSN) will be a transient source of MeV neutrinos that JUNO can detect. The potential of JUNO to CCSN neutrinos is described in this section.

4.1 Detection in JUNO

Two independent triggers with energy thresholds of $O\,(20\;keV)$ and $O\,(200\;keV)$ will be operating to identify neutrino interactions. The first will provide a stream of time and charge (T/Q) data, while for the latter the full waveform will be available. Moreover, if a CCSN event is identified, the detector will be read out in trigger-less mode during the CCSN duration. With its large target mass, JUNO is expected to observe $\sim 10^4$ events for a core collapse supernova at 10 kpc. Similar to Cherenkov detectors, the dominant channel will be inverse beta decay, IBD. Additionally, JUNO is sensitive to other relevant neutrino interaction channels, such as elastic scattering on hydrogen (protons) and electrons. Neutral and charged current inelastic scatterings with carbon are expected as well, even though subdominant. Thus, JUNO will be sensitive to neutrinos of all flavors via the different interaction channels. In fact, JUNO brings the possibility to collect a high-statistics sample of proton scattering events (~1000 events at 5 kpc for the $O\,(200\;keV)$ trigger), neutral current (NC). This channel is particularly beneficial to disentangle neutrino flavor composition as NC interactions are insensitive to neutrino flavor conversion effects.

4.2 Real-time monitoring

First of all, we want to identify the signal burst. For that, a continuous monitoring of the JUNO data will be performed in real time, searching for a localised increase of the detection rates in time. Two different strategies will be used to trigger on a CCSN event: the first is based on a bayesian block algorithm [8], and the other on a sliding trigger window method. The online supernova (SN) monitor system is integrated in the DAQ. A software trigger is in charge of building physics events from the trigger-less T/Q data stream in real time. Then, the vertex and energy information provided by the online reconstruction algorithms are used to select IBD events as SN neutrino candidates. Alternatively, a prompt monitor operates directly at hardware level and selects CCSN by using a cut in the visible energy (8 MeV $<E_{vis}<$40 MeV) instead of relying in the IBD coincidence selection, which makes its response faster. Even though for reference Galactic events (10 kpc) the background level in JUNO is negligible, this is not the case for distant CCSN where one aims to determine which is the detection sensitivity horizon. A careful evaluation of the different background contributions has been carried out to compute the false alert rate. In particular, the water pool triggers are used as a veto to reject the muon-induced cosmogenic background. Fig. 5 shows the alert efficiency as a function of the distance to the source, showing that JUNO will be able to trigger on >90% of the CCSN events below 200-300 kpc, depending on the model.

4.3 Pointing

One key information about the next explosion that neutrino detectors can provide is pointing to the source. There are two common ways to go when one searches to determine the source location: the first is using triangulation (the delay of the signal between different experiments on Earth)

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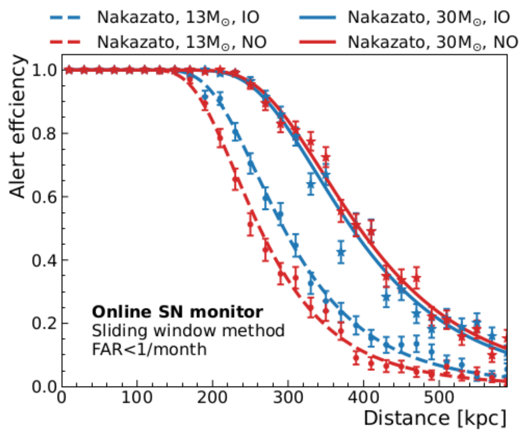

Figure 5: Alert efficiency of the online SN monitor as function of the distance to the source, using the sliding window method. Two different progenitor masses are considered, as well as the normal and inverted neutrino mass ordering scenarios. Figure extracted from [9]

to define a sky region, and the second are anisotropic interactions, where the product particles give information about the neutrino direction, which points back to the source. JUNO is one the detectors able to go for the second method on its own. In fact, the direction given by the vertexes of the reconstructed positron and neutron capture in IBD interactions, provides a good estimate of the neutrino direction. This is due to two facts: i) the emitted neutrons of IBD interactions are slightly forward scattered and ii) the positron annihilates almost at the same point it is produced (average displacement $O(0.1$ cm) negligible compared to vertex resolution (few cm)). The expected performance of JUNO is shown in Fig. 6.

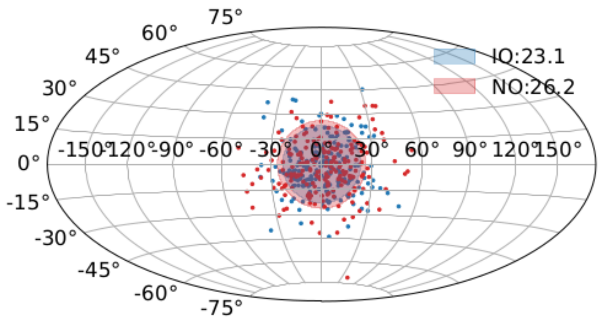

Figure 6: Skymap of the reconstructed CCSN localisation. The shaded region represents the the 68% CL area, for a CCSN with Galactic coordinates (0,0). The points represent 200 realisations of a CCSN simulated for each neutrino mass ordering hypothesis (inverted in blue, normal in pink). Figure taken from [9].

4.4 Flavor-by-flavor energy spectrum reconstruction

Through the three main interaction channels described in section 4.1, JUNO can detect all flavor neutrino fluxes from a CCSN. With its capability to separate the different channels and its good energy resolution, JUNO has the potential to reconstruct the energy spectra of all flavors. The IBD channel can be identified via the coincidence between the prompt and delayed signals, while ES interactions on protons and electrons give a single trigger. Moreover, the proton and electron recoil have a different visible energy spectrum. With a dedicated selection, one can have a precise channel classification in JUNO.

The relationship between observed spectra of the three main channels (IBD, eES and pES) and the initial neutrino fluxes for each flavor can be modeled as: $S = A\dot{F}$, where A is the response matrix reflecting the detector response, F is the flavor dependent neutrino energy spectrum, and S is the observed spectra per detection channel. With this linear correspondence, an unfolding procedure is applied to obtain the reconstructed flavor-by-flavor neutrino spectrum in a model independent approach. Fig. 7 shows the unfolding result for a CCSN at 10 kpc. This result is taken from [10], where a toy monte-carlo was used to evaluate the JUNO performance, as an illustration.

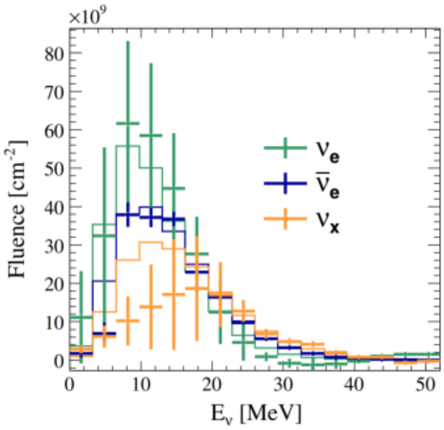

Figure 7: Reconstructed neutrino spectrum for each neutrino flavor, assuming a SN at 10 kpc. Fig. from [10].

5. Conclusions

This paper shows the capabilities of JUNO to study different astrophysical neutrino sources, showing that JUNO will be key in many different physics aspects: resolving unknowns in solar physics such as the metallicity problem, unveiling and constraining the diffuse supernova neutrino background, and contributing to improving our knowledge on CCSN physics and CCSN neutrinos. Moreover, its outstanding reconstruction performance and high event statistics will allow to have more precise flux measurements from these sources compared to the current observations.

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