PROCEEDINGS OF SCIENCE

Prospects for Neutrinos from Natural Sources in JUNO

Elisa Percalli[a,b,*] **on behalf of the JUNO collaboration**

[a] *Università degli studi di Milano, Milan, Italy*
[b] *INFN, Sezione di Milano, Milan, Italy*

E-mail: elisa.percalli@mi.infn.it

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20-kiloton liquid scintillator detector nearing completion in southern China. JUNO is designed to achieve an energy resolution of 3% at 1 MeV, with its primary goal being the determination of the neutrino mass ordering by resolving fine structures in the antineutrino energy spectrum from nearby nuclear reactors. Additionally, with its large scale, extensive PMT coverage, and low background, JUNO will carry on a broad physics program, detecting neutrinos with energies from keV to GeV. JUNO will perform neutrino oscillation measurements using atmospheric neutrinos, increasing its sensitivity to mass ordering. It will further investigate solar neutrinos, geoneutrinos, and neutrinos from supernova bursts, contributing to the study of the physics of their sources. This talk will focus on JUNO's physics potential with neutrinos from natural sources.

The 43rd International Symposium on Physics in Collision (PIC2024)
22–25 October 2024
Athens, Greece

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) All rights for text and data mining, AI training, and similar technologies for commercial purposes, are reserved. ISSN 1824-8039 . Published by SISSA Medialab.

PoS(PIC2024)029

1. JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) is an experiment currently under construction in China, built for the detection of reactor antineutrinos, to determine the neutrino mass ordering [1]. The detector is now in the final stages of construction and it will start data-taking in 2025. The detector is located in a laboratory 700 m deep underground, to shield from cosmic muons, at a distance of 53 km away from two nuclear power plants in the south of China (Taishan NPP and Yangjiang NPP). This distance has been chosen to maximize the difference between the antineutrinos survival probability for the two possible orderings of the masses (normal and inverted). JUNO central detector is made of 20 ktons of organic liquid scintillator (LS) contained in a 17.7 meter radius acrylic sphere. The sphere is surrounded by 17612 20" PMTs and 25600 3" PMTs for a total optical coverage of 78%. The Central Detector is located in a water pool which, along with a system of PMTs oriented outward and a plastic scintillator top tracker, functions as a muon tracker. Thanks to its big volume and unprecedented energy resolution of 3% at MeV, JUNO has the potential of determining the correct neutrino mass ordering in 7 years with a 3 σ sensitivity, and improve the current measurements on the oscillation parameters [2] [3]. JUNO's good features make it also a powerful detector for measuring neutrinos from various natural sources.

1.1 Atmospheric Neutrinos

Atmospheric neutrinos are produced in the Earth's atmosphere as secondary particles from cosmic ray interactions with atmospheric nuclei. These interactions generate extensive air showers, where mesons (K, π) and muons subsequently decay, producing neutrinos and antineutrinos of all flavors.

One of the most important applications in detecting atmospheric neutrinos is that they can be used to determine the neutrino mass ordering (NMO). As these neutrinos propagate through the Earth, their oscillation probabilities are influenced by the matter effects induced by coherent forward scattering on electrons. This effect, described by the MSW (Mikheyev-Smirnov-Wolfenstein) mechanism, leads to an enhancement of the oscillation probability for neutrinos in the normal mass ordering (NO) scenario and for antineutrinos in the inverted mass ordering (IO). This effect is enhanced in the region of a few GeV and $\cos(\theta) < -0.8$, with an expected signal of 10/15 events per day. The main challenge of this analysis is the flavor identification useful to identify electron neutrinos, which are the channels with the highest sensitivity to NMO.

The detection of atmospheric neutrinos in JUNO opens another channel for the determination of the neutrino mass ordering, with lower significance, but in an independent way. The combination of the two measurements could improve the mass ordering determination by providing independent constraints. [4].

1.2 Solar Neutrinos

Solar neutrinos are produced in nuclear reactions, that are responsible for hydrogen burning in the Sun's core. The solar neutrino spectrum extends from a few keV to tens of MeV, corresponding to different reaction channels.

The low-energy region of the spectrum is dominated by pp solar neutrinos, which are challenging to detect in organic liquid scintillators due to the huge background from ^{14}C, which hides the low

PoS(PIC2024)029

energy region of the spectrum.
The intermediate-energy region, up to approximately 2 MeV, is populated by pep, ^{7}Be, and CNO neutrinos. The primary detection channel in this energy range is elastic scattering on electrons, which produces scintillation light in the detector. However, this signal is easily mimicked by radioactive background sources. For this reason, the radiopurity of the LS will be decisive and a good effort has been made to purify it before filling the detector [5]. Hence the sensitivity study for the detection of solar neutrinos depends on the radiopurity scenario, ranging from the minimum required for neutrino mass ordering (10^{-15} g/g for ^{232}Th and ^{238}U) determination to an optimistic scenario matching Borexino's radiopurity levels (10^{-17} g/g for ^{232}Th and ^{238}U). For all these scenarios JUNO has the potential to improve the current constraints on the ^{7}Be flux within just two years of data taking, as well as on the pep flux, except in the worst-case radiopurity scenario [6]. For CNO neutrinos, a longer data-taking period will be required, ranging from 2 to 6 years depending on the radiopurity level.
The high-energy region of the spectrum is dominated by ^{8}B neutrinos, which can also be detected via their interactions with ^{13}C, together with scattering reaction on electrons. This allows for a simultaneous measurement of the ^{8}B flux and the solar oscillation parameters, θ_{21} and Δm^2_{21}, that will also be determined through reactor neutrino measurements [7] [8]. This will allow a more robust measurement of these parameters, thanks to a combined analysis.

1.3 Geoneutrinos

Geoneutrinos are electron antineutrinos ($\bar{\nu}_e$) produced by the radioactive decays of long-lived isotopes within the Earth, primarily from the Uranium (^{238}U) and Thorium (^{232}Th) decay chains in the crust and mantle. Their detection provides an opportunity to probe the Earth's radiogenic heat production, offering insights into fundamental geophysical processes such as mantle convection, plate tectonics, and the generation of the Earth's magnetic field. In particular, measuring the relative abundances of Uranium and Thorium through their neutrino emissions can help constrain models of Earth's formation and differentiation. For JUNO's main goal, geoneutrinos represent a background, as they share the same inverse beta decay (IBD) detection channel. Disentangling the geoneutrino signal from reactor neutrinos is the main challenge of this measurement, also because their energies are in the same region (few MeV) and the reactor neutrino flux at JUNO is very high. The proposed analysis technique is the spectral shape analysis since the geoneutrino spectral shape can be studied in advance. Hence it's very important to predict the geoneutrino flux, which depends on the chosen model of the Earth's lithosphere and mantle composition. To reduce uncertainties, many geological studies have been done to refine local crust models, improving the precision of expected flux calculations [9].
The main advantage of JUNO in this measurement is its large mass, which allows it to have a big statistic of approximately 400 geoneutrinos per year, significantly enhancing statistical precision. Since the geoneutrino flux is very low JUNO will be the first experiment to collect such statistics, improving in only one year our current knowledge on neutrinos, with an expected precision of approximately 22% in one year, and 8% in ten years [10].

PoS(PIC2024)029

1.4 Supernova Neutrinos and the Diffuse Supernova Neutrino Background

Core collapse supernovae (CCSNe) are among the most energetic astrophysical events, releasing nearly 99% of their gravitational energy in the form of neutrinos. These neutrinos, produced through various processes such as electron capture, neutronization, and thermal emission, carry crucial information about the dynamics of the explosion, the equation of state of nuclear matter, and neutrino flavor transformations in extreme conditions. JUNO, with its large target mass and high light yield, will be highly sensitive to a nearby supernova burst, detecting thousands of neutrinos from a galactic event within a few tens of kiloparsecs. By analyzing the time, energy, and flavor distribution of the SN neutrinos, JUNO can help the global understanding on the core-collapse mechanism. [11]. Moreover JUNO will be sensitive to pre supernova neutrinos, that are emitted in the days before the explosion and can be very useful to alert other telescopes of the incoming supernova explosion. The favorite channel for the detection is the IBD channel since the signal will have fewer backgrounds. JUNO has the potential of detecting a SN explosion (for a star of $30M_{\odot}$) up to 370 kpc and pre SN neutrinos up to 1.6 kp (for NO).

In addition to detecting neutrinos from an individual supernova event, JUNO aims to observe the Diffuse Supernova Neutrino Background (DSNB), a steady flux of neutrinos originating from all past core-collapse supernovae. The DSNB is an important probe for cosmological parameters like the rate of SN explosions, the average CCSN neutrino energy, and the fraction of failed black hole formations. However, detecting DSNB neutrinos is challenging due to their low flux (expected 0.14 events/y/kton) and energy (in the range of a few to tens of MeV), requiring careful background suppression and event selection techniques [12]. With its 20-kiloton fiducial mass, JUNO is expected to detect several DSNB events per year, significantly improving current experimental limits. The favorite detection channel is the IBD one, but selecting only higher energies (higher than 12 MeV), to avoid overlapping with reactor antineutrinos energies.
Another important background comes from atmospheric neutrinos, which contribute particularly at higher energies. The main strategy for the background suppression will be using a volume cut and the three-fold coincidences technique. The sensitivity analysis is dependent on the chosen model for the DSNB itself, but anyway, JUNO has the possibility of reaching a sensitivity $>3\sigma$ in 10 years of data taking. Even if there is no positive detection of DSNB, JUNO can still put competitive limits on its flux improving our current knowledge.
JUNO's sensitivity to both real-time supernova bursts and the DSNB will open new possibilities in astrophysical and cosmological studies.

Conclusions

The Jiangmen Underground Neutrino Observatory (JUNO) has the potential to give significant contributions to the field of neutrino physics by detecting neutrinos from various natural sources. Thanks to its large 20-kiloton liquid scintillator detector, excellent energy resolution, and low energy threshold, JUNO will be able to observe and study neutrinos produced in astrophysical, geophysical, and atmospheric processes with unprecedented precision.

PoS(PIC2024)029

JUNO's capability to detect solar neutrinos, particularly from the ^{7}Be, *pep*, and CNO reactions, will provide critical insights into solar fusion processes and neutrino oscillations in the Sun. Its high statistics and precise measurements will improve constraints on solar models and neutrino flavor conversion mechanisms. Additionally, the detection of ^{8}B neutrinos through interactions with ^{13}C will allow simultaneous measurements of the flux and oscillation parameters, offering a cross-check with reactor neutrino oscillation results.

Geoneutrinos from radioactive decays in the Earth's crust and mantle will provide valuable information about the planet's internal heat generation and composition. JUNO's high event rate of approximately 400 geoneutrinos per year will allow precise determination of the Uranium-to-Thorium ratio and total radiogenic heat contribution.

The detection of atmospheric neutrinos will offer an independent probe of neutrino oscillations. Matter effects in the Earth's interior will enhance JUNO's sensitivity to neutrino mass ordering (NMO), especially when combined with reactor neutrino data.

Finally, JUNO is expected to play a crucial role in supernova neutrino detection, enabling real-time observation of neutrinos from a core-collapse supernova within our galaxy. Furthermore, JUNO's sensitivity to the Diffuse Supernova Neutrino Background (DSNB) will allow the first statistically significant measurement of relic neutrinos from past supernovae, shedding light on the history of stellar evolution and core-collapse rates.

References

[1] A. Abusleme et al. (JUNO Collaboration). "JUNO physics and detector". In: *Progress in Particle and Nuclear Physics* 123 (2022), p. 103927. DOI: https://doi.org/10.1016/j.ppnp.2021.103927.

[2] A. Abusleme et al. (JUNO Collaboration). "Sub-percent precision measurement of neutrino oscillation parameters with JUNO*". In: *Chinese Physics C* 46.12 (Dec. 2022), p. 123001. DOI: 10.1088/1674-1137/ac8bc9. URL: https://dx.doi.org/10.1088/1674-1137/ac8bc9.

[3] A. Abusleme et al. (JUNO Collaboration). *Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO*. 2024. arXiv: 2405.18008 [hep-ex].

[4] A. Abusleme et al. (JUNO Collaboration). "JUNO sensitivity to low energy atmospheric neutrino spectra". In: *The European Physical Journal C* 81.10 (Oct. 2021). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-021-09565-z.

[5] C. Landini et al. "Distillation and gas stripping purification plants for the JUNO liquid scintillator". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1069 (2024), p. 169887. DOI: https://doi.org/10.1016/j.nima.2024.169887.

[6] A. Abusleme et al. (JUNO Collaboration). "JUNO sensitivity to 7Be, pep, and CNO solar neutrinos". In: *Journal of Cosmology and Astroparticle Physics* 2023.10 (Oct. 2023), p. 022. DOI: 10.1088/1475-7516/2023/10/022.

PoS(PIC2024)029

[7] Jie Zhao et al. (JUNO Collaboration). "Model-independent Approach of the JUNO 8B Solar Neutrino Program". In: *The Astrophysical Journal* 965.2 (Apr. 2024), p. 122. DOI: 10.3847/1538-4357/ad2bfd. URL: https://dx.doi.org/10.3847/1538-4357/ad2bfd.

[8] A. Abusleme et al. (JUNO Collaboration). "Feasibility and physics potential of detecting 8B solar neutrinos at JUNO". In: *Chinese Physics C* 45.2 (2021), p. 023004. DOI: 10.1088/1674-1137/abd92a.

[9] Virginia Strati et al. "Expected geoneutrino signal at JUNO". In: *Progress in Earth and Planetary Science* (Dec. 2015). DOI: 10.1186/s40645-015-0037-6.

[10] A. Abusleme et al. (JUNO Collaboration). "Neutrino physics with JUNO". In: *Journal of Physics G: Nuclear and Particle Physics* 43.3 (Feb. 2016), p. 030401. DOI: 10.1088/0954-3899/43/3/030401. URL: https://dx.doi.org/10.1088/0954-3899/43/3/030401.

[11] A. Abusleme et al. (JUNO Collaboration). "Real-time monitoring for the next core-collapse supernova in JUNO". In: *Journal of Cosmology and Astroparticle Physics* 2024.01 (Jan. 2024), p. 057. DOI: 10.1088/1475-7516/2024/01/057. URL: https://dx.doi.org/10.1088/1475-7516/2024/01/057.

[12] A. Abusleme et al. (JUNO Collaboration). "Prospects for detecting the diffuse supernova neutrino background with JUNO". In: *Journal of Cosmology and Astroparticle Physics* 2022.10 (Oct. 2022), p. 033. DOI: 10.1088/1475-7516/2022/10/033. URL: https://dx.doi.org/10.1088/1475-7516/2022/10/033.

PoS(PIC2024)029