Supernova's neutrino detection at the Jiangmen Underground Neutrino Observatory

C. Lombardo on behalf of the JUNO collaboration

Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via S. Sofia, 64, 95123 Catania (Italy)

E-mail: `claudio.lombardo@phd.unict.it`

Abstract. The Jiangmen Underground Neutrino Observatory (JUNO) will be the largest ever built liquid scintillator detector for neutrino physics. JUNO is a 20 kton liquid scintillator detector, equipped with 20012 large PMTs and 25600 small PMTs. It will be sensitive to various neutrino sources and will give a unique contribution to the observation of the all-flavor neutrino flux from a Galactic core collapse supernova (CCSN). JUNO can detects neutrinos emitted by the next CCSN neutrinos through several interactions, among which inverse beta decay, elastic scattering on electron and proton can providing information of energy spectra of all flavors. Furthermore, JUNO will be able to provide an alert during the pre-SN phase. In this manuscript, the observatory detectors and its capability to detect CCSN neutrinos will be presented.

1. Introduction

The explosion of the massive core-collapse supernova (CCSN) is one of the most powerful astrophysical phenomena in the Universe and most of this energy is released in the form of neutrinos and antineutrinos. Galactic SuperNovae (SNe) are rather rare [1], therefore the chance of a detection during the lifetime of an experiment is low. Moreover, the probability of detection depends on the Earth-SN distance. To increase the probability of detecting the next SN, JUNO will use a specially developed trigger system and will join forces with SNEWS (SuperNova Early Warning System). In addition, several studies based on Monte Carlo simulations have been carried out, leading JUNO to play a key role among the neutrino detectors of the current generation. The Jiangmen Underground Neutrino Observatory (JUNO) [2], which is under construction in South China and will be online in 2023, would be the largest ever liquid scintillator (LS) based detector increasing the number of events from CCSN.

2. Core Collapse SuperNova and neutrino emission

Neutrino emission from massive stars commences early from the fusion of hydrogen and becomes the dominant source of stellar cooling over photon radiations following the ignition of carbon [3]. Starting from the phase of carbon burning, neutrinos are dominantly produced in pairs through thermal processes, in example the plasma decay ($\gamma^* \to \nu + \overline{\nu}$), the photo process ($\gamma + e^- \to e^- + \nu + \overline{\nu}$), the pair process ($e^+ + e^- \to \nu + \overline{\nu}$) and the bremsstrahlung ($e^- + Ze \to Ze + \nu + \overline{\nu}$). The contribution from nuclear weak interactions to neutrinos, including electron capture and beta decays of heavy nuclei, becomes important after the silicon

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

burning [4] [5].
Prior to the core collapse, the luminosities and average energies of these neutrinos ν_e, $\overline{\nu}_e$ and ν_x (x stands for μ or τ), called pre-SN neutrinos, increase dramatically during weeks before the explosion [6]. At the end of the stellar evolution of massive stars, a burst of neutrinos of higher luminosities and average energies than pre-SN neutrinos, called SN burst neutrinos, are emitted. These SN burst neutrinos are not obscured by interstellar dust, not deviated by galactic electromagnetic field, nor totally absent with failure explosions into black holes, which highlights the importance of neutrino detection for presage of the next CCSN. The pre-SN neutrinos and SN burst neutrinos undergo flavor conversions when propagating from the stellar core to terrestrial detectors. As shown in [4] [7], the Mikheyev-Smirnov-Wolfenstein (MSW) matter effects for both pre-SN and SN neutrinos are highly adiabatic and dependent on the neutrino mass ordering. The neutrinos fluxes F_ν at the earth can be expressed in terms of the initial flux $F_{0\nu}$ at production [8]:

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)\,F^0_{\nu_x} \tag{1}$$

$$F_{\overline{\nu}_e} = pF^0_{\overline{\nu}_e} + (1-p)\,F^0_{\overline{\nu}_x} \tag{2}$$

$$F_{\nu_x} = 0.5\,(1-p)\,F^0_{\nu_e} + 0.5\,(1+p)\,F^0_{\nu_x} \tag{3}$$

$$F_{\overline{\nu}_x} = 0.5\,(1-p)\,F^0_{\overline{\nu}_e} + 0.5\,(1+p)\,F^0_{\nu_x} \tag{4}$$

3. JUNO

JUNO [9] is a neutrino observatory under construction in China. JUNO measures the neutrino flux from 8 reactor cores dispatched in two nuclear power plants (combined thermal power of 26.6 GW). The primary goals are to determine the correct neutrino mass ordering and perform precise measurements on oscillation parameters [10]. To improve the sensibility on Mass Ordering a reference detector will be placed close to one core of the Taishan Nuclear Power Plants named TAO, *Taishan Antineutrino Observatory* [11]. JUNO is also sensitive to solar neutrinos emitted from different beta decay chain (^7Be, ^8B, pep and CNO) [12], to atmospheric neutrinos [13], to geo-neutrinos, to Diffused SuperNova Neutrino Background [14] and to neutrinos emitted before e during a CCSN.

3.1. Central detector

The main detector of the observatory will be placed 53 km away from two nuclear power plants, Yangjiang and Taishan, in China, as shown in fig. 1 and it will be 650 m underground to reduce the background due to muons.

The detector (fig. 2), is formed by an acrylic vessel of 35.4 m of diameter filled with liquid scintillator (LS) based on: LAB (Lynear Alkyl Benzene), 3 g/L diphenyloxazole (PPO) and 2 mg/L p-bis-(o-methylstyryl)-benzene (bis-MSB). Photons produced by scintillitaion will be collected by 17612 20-inch PMTs and by 25600 3-inch PMTs, all tested and ready to be installed [15], that allows JUNO to perform dual calorimetry measurements. The acrylic vessel with the stainless steel structure and the PMT with the correlated electronic will be surrounded by a water tank instrumented with 2400 20-inch PMTs and will be used as a Cherenkov detector. The water Cherenkov detector and a plastic scintillator placed on the top will work as veto detector to tag the events inducted by external muons. Furthermore, the water tank will shield the central detector from neutrons and from natural radioactivity emitted by the rocks.

Different interacion channels will be used to detect: Inverse Beta Decay (IBD), elastic scattering on electron (eES) or on proton (pES) and weak interactions on ^{12}C. The IBD, $\overline{\nu}_e + p \rightarrow e^+ + n$, is the golden channel due to its characteristic signature, in fact, this events present a first flash of ligh and a second flash delayed by a known amount of time. This signature makes easy to

Figure 1. JUNO is under construction in Guandhong province, 53 km away from two nuclear powerplants. TAO will be placed 30 m away the core of the Taishan NPP.

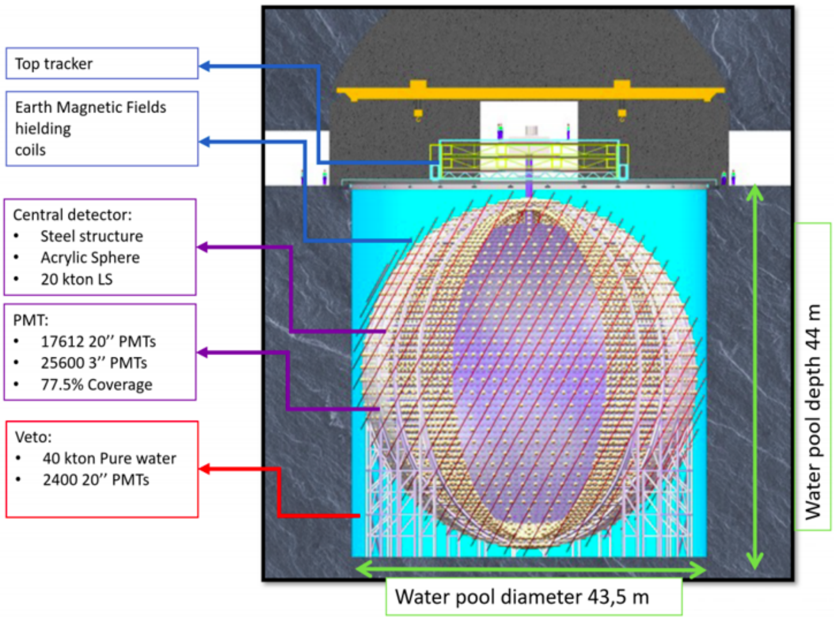

Figure 2. JUNO is a spherical liquid scintillator detector in which photons will be collected by PMTs. A water Cherenkov Detctor and a plastic scintillator, as top tracker, will sorround the central detector as shielding and veto detecor.

distinguish physical events from background but it is sensitive only to electron antineutrinos. To detect other flavours neutrinos only elastic scattering can be used.

3.2. TAO

TAO will make an accurate measurement of antineutrino energy spectrum near the reactor core of the Taishan Nuclear Power Plants with 2%@1MeV accuracy(1.5% statistical uncertainty) to provide a benchmark unoscillated spectrum for JUNO studies on Mass Ordering and oscillations parameters.

TAO is a liquid scintillator detector that detects the electron antineutrinos via the Inverse Beta Decay (IBD) similar to the main detector of JUNO. The schematic drawing of the TAO detector is presented in fig. 3. The detector consists of 2.8 ton gadolinium-doped LS filled in a spherical acrylic vessel and viewed by SiPMs (∼ 4000), a spherical copper shell that supports the SiPMs, a liquid scintillator buffer, and a cylindrical stainless steel tank insulated with 20 cm thick Polyurethane. The outer shielding includes a water tank in the surrounding, High Density Polyethylene on the top, and lead at the bottom. The water tanks, instrumented with Photomultipliers (shown by red circles), and the Plastic Scintillator on the top comprise the active muon veto system necessary for the ground based detector.

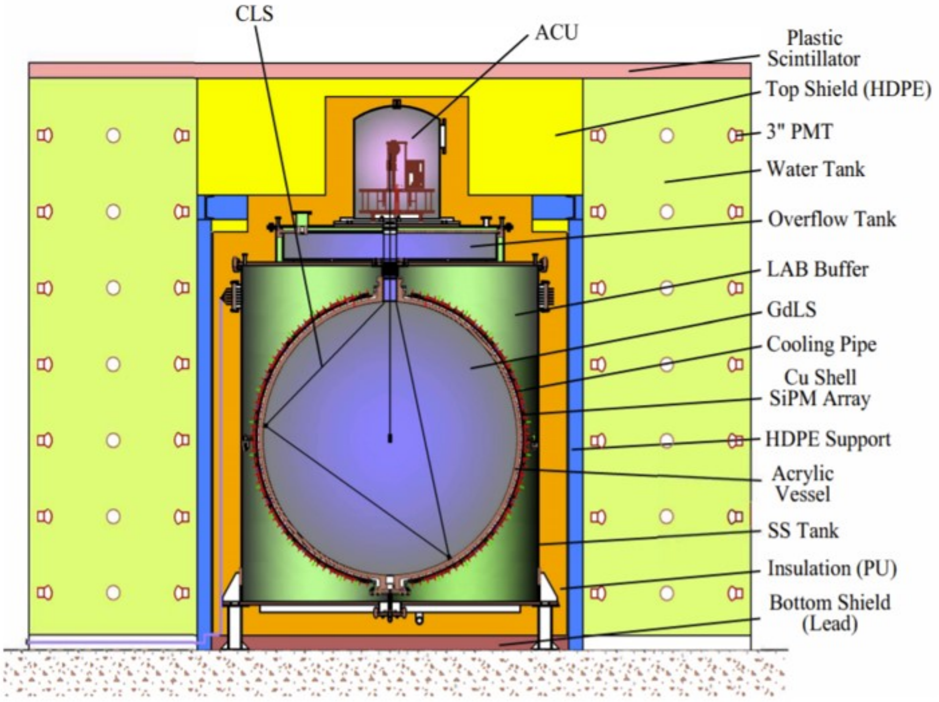

Figure 3. Schematic view of the TAO detector, consisting of a Central Detector (CD), the cryogenic system, an outer shielding and veto system.

To reduce the thermal noise of SiPMs, mandatory to reach the energy resolution goal, the detector will operate at -50 °C.

The liquid scintillator was obtained starting from the formula of the LS used in JUNO optimized for low temperatures.In particular, TAO will use: LAB (Lynear Alkyl Benzene) doped with Gadolinium, 3 g/L diphenyloxazole (PPO), 2 mg/L p-bis-(o-methylstyryl)-benzene (bis-MSB) and a small fraction of Ethanol.

4. SN detection

SN burst neutrinos of several tens MeV could be registered with full flavors in LS via different channels: inverse beta decay, neutrino-proton elastic scattering, neutrino-electron elastic scattering, as well as neutral-current and charge-current interactions of neutrinos on carbon nuclei. For a SN at 10 kpc and typical SN parameters, JUNO will register ∼ 5000 IBD events, ∼ 300 eES events, ∼ 2000 pES events and ∼ 500 events on ^{12}C [9]. The energy spectra are shown in fig.4. Pre-supernova neutrinos, detectable via the IBD and eES channels, could

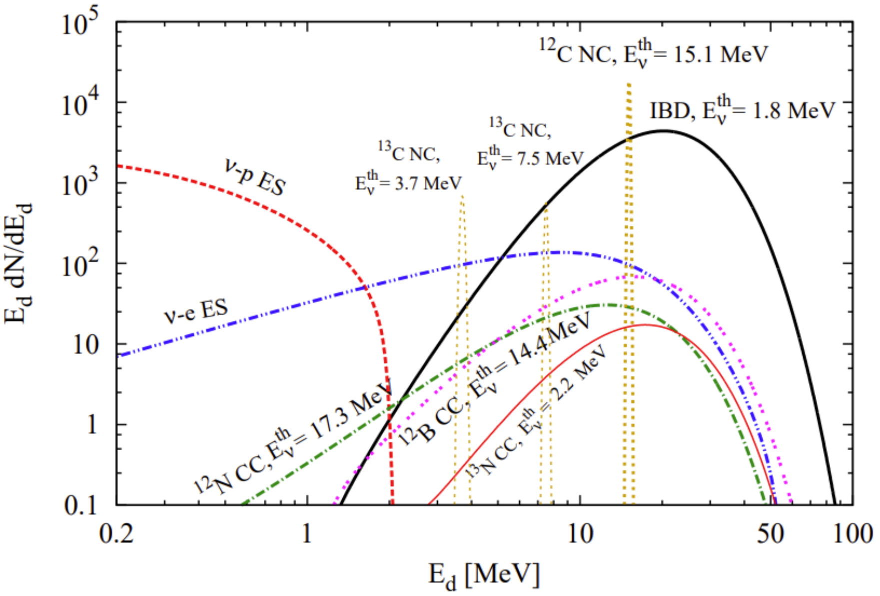

Figure 4. The neutrino event spectra with respect to the visible energy E_d in the JUNO detector for a typical SN at 10 kpc (Ref. [9]).

provide a early warning for the optical observations of core-collapse SNe. The real-time CCSN monitor system in JUNO aims to provide early alerts for the next galactic or nearby galactic CCSN and record CCSN-related data as much as possible.

The IBD candidates for Pre-SN Monitor (pre-SN IBD) are preliminarily selected with fiducial volume cut $r < 17.2$ m and prompt energy cut 0.7 MeV $< E_p <$ 3.4 MeV, delayed energy cut 1.9 MeV $< E_d <$ 2.5 MeV, time interval between the prompt and delayed signal $\Delta T < 1.0$ ms and the prompt-delayed distance cut $R_{p-d} < 1.5$ m. The IBD candidates for SN are selected with the same pre-SN IBD criteria except for a different prompt energy cut $E_p >$ 0.7MeV. Since SN burst neutrinos only lasts for few seconds, the muon veto criteria for pre-SN IBD is not feasible to SN IBD any more. All candidate events can be monitored in real time to provide early alerts for the next CCSN and in case of SN-alert the system will acquire data in trigerless mode to maximize the physical events collected.

5. Diffused SuperNova Neutrino Background

Pre-SN neutrinos are less energetic than SN-neutrinos, consequently, the interactions of neutrinos on carbon nuclei are absent and the recoiled protons of pES are severely quenched in LS [16] to a rather low energy, which makes it challenging for JUNO to record them. These implies than only IBD and eES events are available for pre-SN neutrinos. A careful study on the background was performed to better identify DSNB events, to this scope JUNO will use pulse shape discrimination (PSD) and triple coincidence (TC) cuts. The dominant background is from the neutral-current (NC) interaction of atmospheric neutrinos with ^{12}C nuclei, which surpasses the DSNB signal by more than one order of magnitude. Different types of particles depositing energies in LS will have distinct photon emission time profiles, therefore, the PSD technique will be powerful to distinguish the backgrounds with different profiles of time distributions. The spectrum after all the cuts is visible in fig. 5. JUNO can reach the significance of 3σ after 3 years of data taking and 5σ after 10 years. Even for the pessimistic scenario with non-observation, JUNO would strongly improve the current limits of the DSNB model.

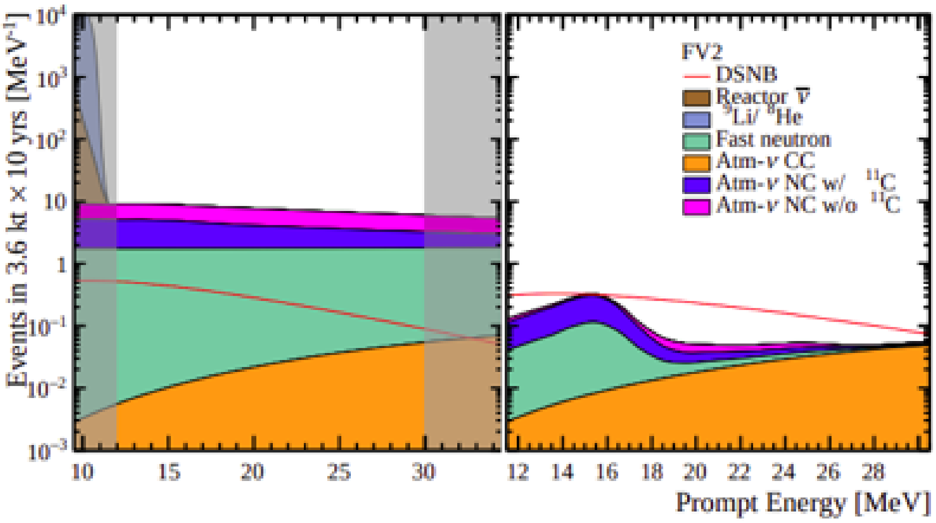

Figure 5. The DSNB energy spectrum versus all backgrounds before (left) and after cuts (right) [14].

6. Conclusion

JUNO will complete the detector construction in 2023 and start starts its rich physics program. JUNO will obtain a high-statistics measurement of the neutrino emitted by the two nuclear power plants. JUNO will provide a deep insights into the supernova burst mechanism and with 10 years of data, it is expected to provide a 5σ evidence of the DSNB signal

Acknowledgement

My attendance to this Conference would not have been possible without the financial support of the “Università degli Studi di Catania”; in particular, thanks to the funds PIA.CE.RI-Linea 2 2020-2022, Research Project “MAYORANA”, Principal Investigator Prof. Rossella Caruso.

References

[1] Rozwadowska K, Vissani F and Cappellaro E 2021 *New Astronomy* **83** 101498
[2] An F *et al.* 2016 *Journal of Physics G: Nuclear and Particle Physics* **43** 030401
[3] Woosley S E *et al.* 2002 *Reviews of modern physics* **74** 1015
[4] Kato C *et al.* 2017 *The Astrophysical Journal* **848** 48
[5] Yoshida T and Tothers 2016 *Physical Review D* **93** 123012
[6] Patton K M *et al.* 2017 *The Astrophysical Journal* **851** 6
[7] Duan H and Kneller J P 2009 *Journal of Physics G: Nuclear and Particle Physics* **36** 113201
[8] Dighe A S and Smirnov Y A 1999 *Phys. Rev. D* **62** 033007
[9] Abusleme A *et al.* 2021 *Progress in Particle and Nuclear Physics* 103927
[10] Abusleme A *et al.* 2022 *arXiv preprint arXiv:2204.13249* ,to appear in Chin.Phys.C
[11] Abusleme A *et al.* 2020 *arXiv preprint arXiv:2005.08745*
[12] Abusleme A *et al.* 2021 *Chinese Physics C* **45** 023004
[13] Abusleme A *et al.* 2021 *The European Physical Journal C* **81** 1–16
[14] Abusleme A *et al.* 2022 *arXiv preprint arXiv:2205.08830* ,to appear in Journal of Cosmology and Astroparticle Physics
[15] Abusleme A *et al.* 2022 *arXiv preprint arXiv:2205.08629* ,to appear in European Journal of Physics C
[16] Yang M *et al.* 2019 *Radiation Detection Technology and Methods* **3** 1–6