JUNO Experiment: Detector Status and Physics Opportunities

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Abstract

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment currently under construction in South China. The detector consists of a 35.4 m diameter acrylic sphere filled with 20 000 t of ultra-pure liquid scintillator and makes JUNO the largest liquid scintillator-based, underground neutrino observatory capable of addressing many important topics in different fields of neutrino physics. The primary goal of JUNO is to determine the neutrino mass ordering with a significance greater than 3-4σ after six years of data taking and to perform high-precision measurement of neutrino oscillation parameters. This will be achieved by exploiting the electron antineutrinos emitted by the Yangjiang and Taishan nuclear power plants located about 53 km away from the experimental site, together with the precise measurement of the reactor antineutrino energy spectrum provided by its satellite detector, the Taishan Antineutrino Observatory, located at about 30 m from a reactor core of the Taishan plant. The JUNO central detector will be equipped with 17612 20-inch and 25600 3-inch photomultiplier tubes to provide a photocathode coverage of 78% and an energy resolution better than 3% at 1 MeV with an absolute energy scale uncertainty lower than 1%. The central detector hall will be filled with ultra-pure water to shield the environmental radioactivity and act as a water Cherenkov detector for cosmic muons tagging. Thanks to its excellent characteristics in terms of an unprecedented active mass and excellent energy resolution, the extensive physics program of JUNO comprises also solar neutrinos, atmospheric neutrinos, supernova neutrinos, and geo-neutrinos, as well as beyond Standard Model physics topics such as nucleon decay. The detector construction is expected to be completed in 2024. In this paper I review the current status of the detector and the physics topics covered by JUNO.

Keywords: neutrino physics, neutrino mass ordering, neutrino oscillation, liquid scintillator detector
DOI: 10.31526/BSM-2023.3

1. INTRODUCTION

Neutrino physics is one of the most active fields in particle physics. The current knowledge about neutrino physics, in particular all the parameters associated with oscillations, has been obtained by numerous neutrino experiments that measured solar, atmospheric, accelerator, and reactor neutrinos or antineutrinos. All the experimental results are fully described assuming the existence of three different mass eigenstates that follow the normal or inverted mass ordering. Although the data provided by the oscillation experiments allowed the mixing parameters to be determined with quite good precision, there are many important missing information about them and in neutrino physics in general that are going to be studied by future experiments. The considerable value of θ_{13} allows the medium baseline reactor experiments, placed at the maximum of the solar oscillation probability, to discriminate the two possible mass ordering scenarios by measuring the small oscillation pattern in the antineutrino spectra. The Jiangmen Underground Neutrino Observatory (JUNO) is a massive multipurpose underground neutrino observatory approved in 2013 and currently in the final stage of construction in the south of China [1]. Its main physics goal is the determination of the neutrino mass ordering by measuring the spectrum of the oscillated antineutrinos emitted from six 2.9 GWth and two 4.6 GWth reactor cores in the Yangjiang and Taishan nuclear power plants (NPPs), respectively. The JUNO detector is placed at a baseline of about 53 km from the nuclear power plants to achieve the best sensitivity to neutrino mass ordering measurement, as shown in Figure 1.

To achieve its goal, JUNO relies on a precise measurement of the oscillated reactor antineutrino spectrum shape made possible by strict requirements on the performance of the detector. Moreover, JUNO will be supported by a satellite detector, called Taishan Antineutrino Observatory (TAO) [2], installed at a short distance from the core one of the Taishan plant to provide a very precise measurement of the unoscillated antineutrino spectrum. Thanks to its excellent expected performances JUNO has a rich scientific program that covers many crucial open issues of neutrino and astro-particle physics.

2. JUNO DETECTOR STRUCTURE AND STATUS

The JUNO detector consists of a Central Detector (CD), a water Cherenkov detector (WCD), in which the CD is submerged, and a muon tracker (Top Tracker, TT) placed on top of them, as shown in Figure 2. The civil construction was completed at the end of 2021 and the construction of the detector is ongoing and it is expected to be completed in 2024.

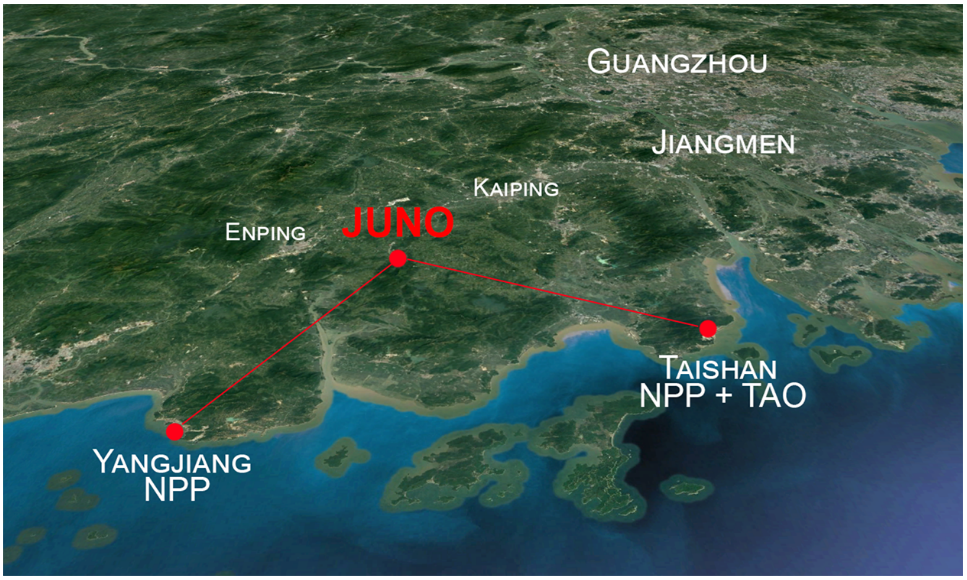


FIGURE 1: JUNO experiment location in the South of China.

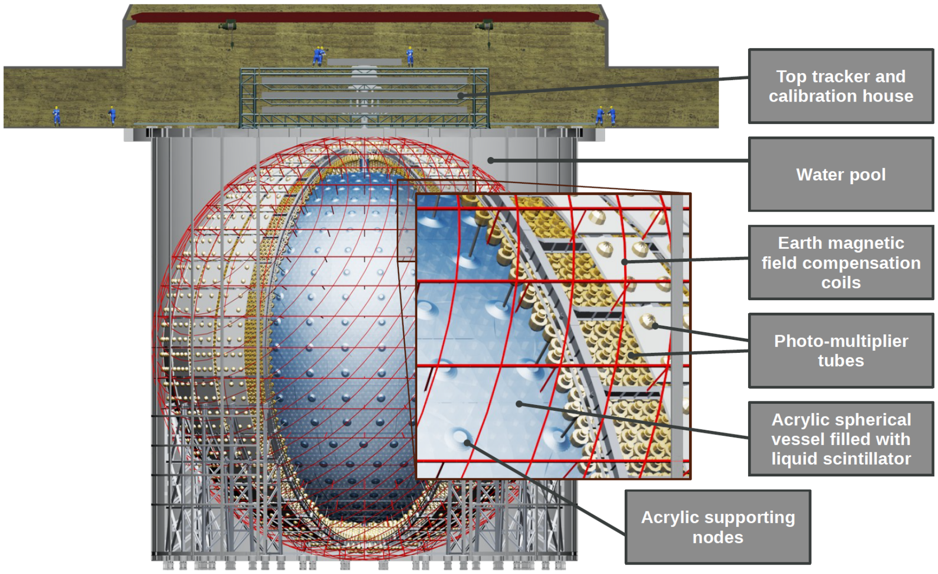
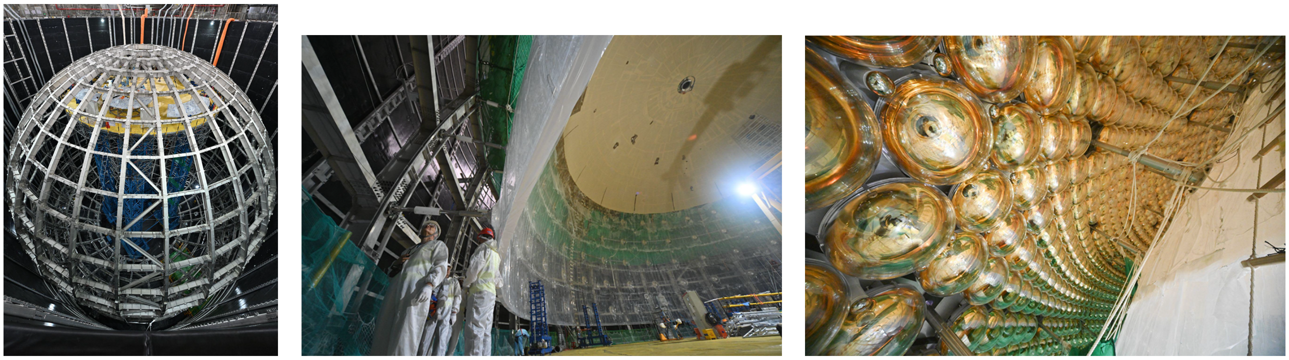


FIGURE 2: Structure of the JUNO detector.

2.1. *Central Detector*

The CD consists in 20 000 t of liquid scintillator contained in a spherical acrylic vessel with an inner diameter of 35.4 m and a thickness of 12 cm. The acrylic is characterized by very high transparency, greater than 96%, and high radiopurity, less than 1 ppt for ^{238}U, ^{232}Th, and ^{40}K. The acrylic vessel is supported by a spherical stainless steel (SS) structure with an inner diameter of 40.1 m, sitting on 30 pairs of stainless steel legs safely rooted to the concrete floor. The scintillation light emitted by the LS is read by 17612 20-inch photomultiplier tubes (LPMTs) and 25600 3-inch photomultiplier tubes (SPMTs), which are installed on the inner side of the SS truss, providing a coverage of 78%. The related electronics is installed underwater close to the PMTs to improve and maximize the signal-to-noise ratio. In order to suppress the Earth magnetic field and to minimize its influence on the photoelectron collection efficiency of the LPMTs, compensation coils are installed. The SS structure was completed in June 2022, as shown in Figure 3(a), followed by the construction of the acrylic sphere. Due to its huge size, the sphere is divided into 256 panels which are produced separately and welded together onsite. The installation started from the top and is currently arrived at layer -1, the first one below the equator (Figure 3(b)). In parallel to the installation of the acrylic panels are installed also the PMTs (Figure 3(c)), which are all produced and tested.



(a) SS truss completed (b) Acrylic panel installation (c) PMTs installation

FIGURE 3: Central detector construction.

2.2. *Liquid Scintillator*

The liquid scintillator is an organic mixture of linear alkylbenzene as solvent, a fluor (PPO, 2.5 g/L), and a wavelength shifter (bis-MSB, 3 mg/L). To fulfill the JUNO requirements, it must have a very high light yield (about 10000 photons/MeV), high attenuation length (>20 m at 430 m) and an extremely high radiopurity level (^{238}U and ^{232}Th $<1 \times 10^{-15}$ g/g and ^{40}K $<1 \times 10^{-16}$ g/g for NMO measurement) [3]. To achieve this result a dedicated purification system was designed. It is composed of four steps: alumina column treatment, distillation, water extraction, and gas stripping. The first step is the alumina column purification used to improve the transparency of LAB. This is followed by distillation in partial vacuum (5 mbar) to remove the heaviest radio-impurities (^{238}U, ^{232}Th, and ^{40}K) and to further improve the optical properties in terms of absorbance and attenuation length. At this point, the PPO and bis-MSB are dissolved into the LAB. The complete LS mixture is then subjected to water extraction to further remove ^{238}U and ^{232}Th, potentially introduced by PPO and bis-MSB. The final step is the stripping, whose main purpose is the removal of radioactive gases and gaseous impurities, using gaseous nitrogen in counter-current flow mode, all performed in partial vacuum at about 250 mbar. The construction of the purification plants is completed and they are currently under commissioning. Before and during the filling, part of the scintillator (about 15%) will be characterized by a dedicated detector named OSIRIS in order to verify the radiopurity constraints.

2.3. *Water Cherenkov Detector and Top Tracker*

The entire CD is submerged in a cylindrical water pool with a diameter of 43.5 m and a height of 44 m, filled with 35 kt of ultrapure water. To prevent ^{222}Rn diffusion from the external rocks from dissolving into the water, 5 mm thick HDPE panels (liner) seal the pool walls and are sustained by a concrete barrier with a minimum thickness of 70 cm placed in front of the cavity rock. The Cherenkov light produced by muons passing through the volume is detected by 2400 LPMTs installed on the outer surface of the SS structure of the CD. In order to guarantee stable performances of the WCD, a water system will provide and monitor the ultra-high purity of the water and ensure temperature uniformity over the whole volume. Finally, on the top of the water pool, a top tracker is installed to precisely measure the muon directions and support the veto strategies with a coverage of about 60%, high granularity and high angular resolution.

3. PHYSICS OPPORTUNITIES WITH JUNO

Thank to its unprecedented characteristic JUNO will be able to address many important topics in neutrino physics. The JUNO experiment's main goal is to determine the neutrino mass ordering (NMO) at 3-4σ level and to provide precision measurement of the oscillation parameters. Besides this, JUNO has the potential to be a multipurpose neutrino observatory by measuring with high sensitivity other neutrino sources such as solar, atmospheric and geoneutrinos and those produced by supernovae explosions. Furthermore, it will provide excellent opportunities for other beyond-SM studies, such as proton decay. In the following section, I'll briefly discuss the main physics channel with the expected sensitivity.

3.1. *Reactor Antineutrino: Mass Ordering and Precision Oscillation Parameters*

The main source of antineutrinos for JUNO will be the two nearby NPPs where the antineutrinos are produced as a consequence of the beta decay of the fission products. The detection channel of JUNO is the Inverse Beta Decay (IBD), in which an antineutrino interacts with a proton of the liquid scintillator to produce a positron and a neutron. This interaction produces a prompt signal resulting from the energy deposition of the positron and its annihilation and a delayed signal produced by the neutron capture after its thermalization. This strong marker allows the background to be rejected with high efficiency by applying constraints on energy, time and position of the vents. In Figure 4 is shown the expected energy spectrum of the reactor antineutrino in the normal and inverted ordering scenarios, together with the unoscillated spectrum.

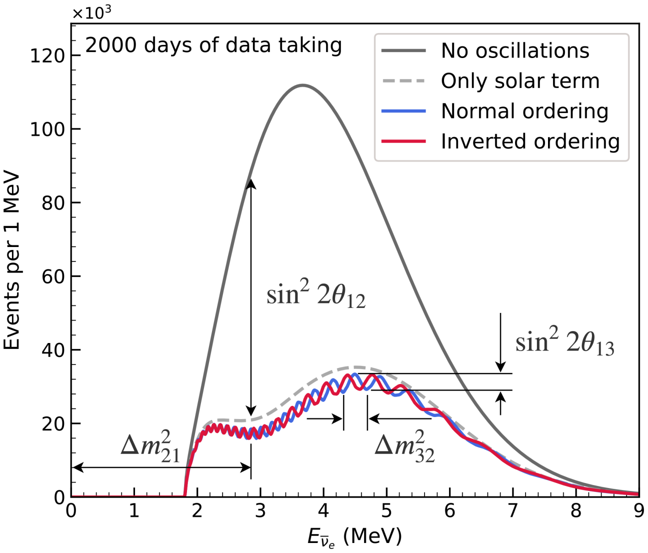
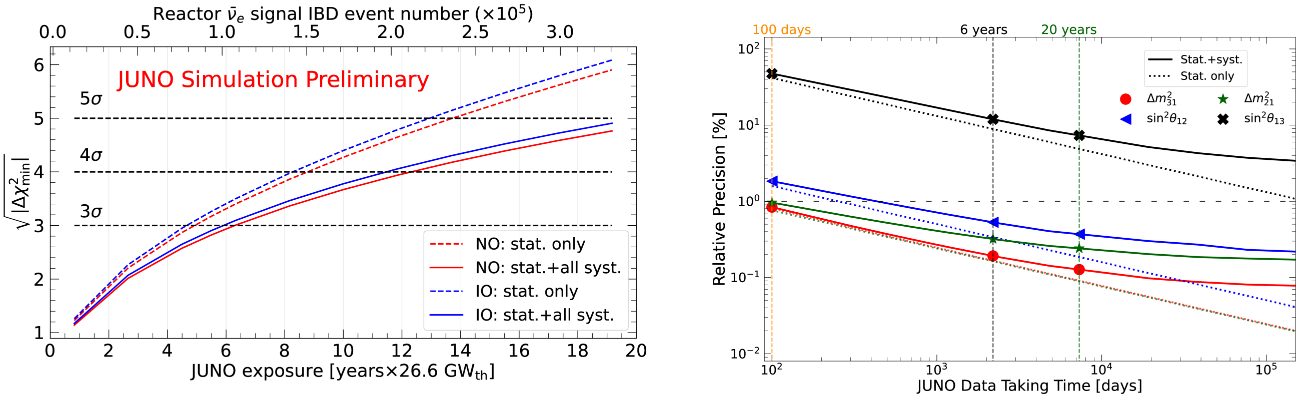


FIGURE 4: Expected antineutrino spectra for normal and inverted ordering with associated oscillation parameters.

The original sensitivity estimation discussed in [1] has been updated accordingly to the changes in the reactor power and detector characteristics. Some changes reduce the expected sensitivity, in particular, the total reactor power is decreased from 35.8 GWth to 26.6 GWth because only two out of 4 reactors at the Taishan NPP were built and the expected muon flux at the detector is increased by 33% because the lower rock overburden. On the contrary, better than expected performances of the detectors are obtained: higher energy resolution (from 3% to 2.9% at 1 MeV), higher muon veto efficiency (from 83% to 91.6%), better radioactive background level [3] and lower unoscillated spectrum uncertainty thanks to TAO detector. In Figure 5(a) is reported the new expected sensitivity for NMO according to these updates as a function of data taking time. JUNO will be able to discriminate the NMO at 3-4σ level in about six years of data taking, including all systematic effects. Furthermore, it is currently under study the possibility of obtaining a higher sensitivity by combining the reactor analysis with that of atmospheric neutrinos.

The JUNO detector will be the first experiment able to observe both the solar and atmospheric oscillations simultaneously being sensitive to the two Δm^2 and to the mixing angle θ_{12} and θ_{13}, as also shown in Figure 4. Thanks to its excellent performances and large statistics, JUNO will be able to measure the oscillation parameters Δm^2_{21}, Δm^2_{32}, and $\sin^2\theta_{12}$ with unprecedented precision, below 0.5% in 6 years of data taking. The precision will reach the sub-percent level in about one year. In Figure 5(b) is shown the expected sensitivity as a function of the data taking time.

More details about mass ordering and precision oscillation parameters measurements can be found in the collaboration papers [4, 5].



(a) NMO expected sensitivity as a function of the data taking time

(b) Oscillation parameters expected sensitivity as a function of the data taking time

FIGURE 5

3.2. *Solar Neutrinos*

Solar neutrinos offer the possibility to investigate many aspects of neutrino physics and solar physics, especially the question of solar metallicity. The JUNO experiment has many advantages in performing solar neutrino measurements compared with previous detectors. It has the benefit of the high resolution and low energy threshold of the LS detectors but with a large mass that allows having large statistics. JUNO will be able to measure all the medium and high-energy solar neutrinos. The sensitivity of JUNO to ^{7}Be, pep and CNO neutrinos strongly depends on the radiopurity of the LS. For this reason, different radiopurity scenarios have been tested, from the worst "IBD scenario" ($\sim 1 \times 10^{-15}$ g/g for ^{238}U, ^{232}Th, and $\sim 1 \times 10^{-16}$ g/g for ^{40}K) up to "Borexino phase III scenario" ($\sim 1 \times 10^{-19}$ g/g for ^{238}U, ^{232}Th, and ^{40}K). Also in the IBD scenario, JUNO will be able to reach the Borexino precision to ^{7}Be neutrinos flux in 1-2 years of data taking and in 6 years for the pep neutrinos. The expected sensitivities as a function of data taking time are shown in Figure 6. The presence of about 200 t of ^{13}C in the LS allows JUNO to provide a model-independent measurement of the flux of ^{8}B neutrinos with a precision of 5% by exploiting charged current and neutral current interactions and elastic scattering on electrons. JUNO will be also able to provide accurate measurement of oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$ with solar neutrinos. JUNO has the potentiality to solve the Δm^2_{21} tension since it will be the first experiment able to measure simultaneously this parameter via reactor and solar neutrinos. More details about solar neutrinos can be found in the collaboration papers [6, 7].

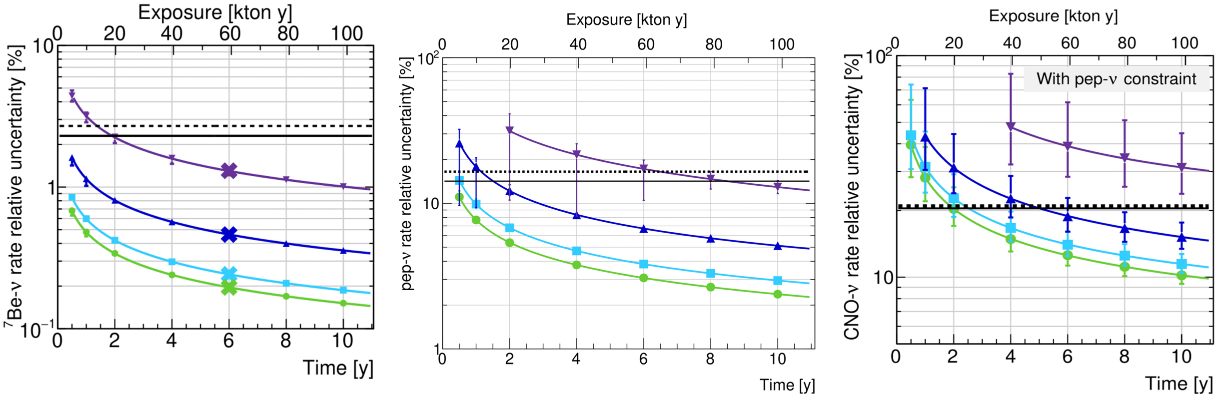


FIGURE 6: ^{7}Be, pep and CNO neutrino fluxes expected sensitivity as a function of the data taking time with different background scenarios.

3.3. *Atmospheric Neutrinos*

Atmospheric neutrinos are a very important source for studying neutrino oscillations. The JUNO mass ordering sensitivity from atmospheric neutrinos is complementary to that from reactor antineutrinos thus the combined sensitivity will exceed the purely statistical combination of the single sensitivities. Furthermore, atmospheric neutrinos allow JUNO to measure θ_{23} mixing angle and study the CP-violating phase. JUNO will be one of the first LS-based detector that will measure atmospheric neutrinos and it will be able to discriminate the neutrino flavor based on the PMTs hit time and waveform feature. Thanks to the large active volume and high energy resolution JUNO will be able to detect several atmospheric neutrinos per day and to reconstruct the energy spectrum with competitive precision, especially in the low-energy region. More details about atmospheric neutrinos can be found in the collaboration paper [8].

3.4. *Supernova Neutrinos*

A core-collapse supernova (SN) emits about 99% of the energy via neutrinos. Thanks to its huge active mass JUNO will be able to detect neutrinos of all flavours in different interaction channels with high statistics for a SN explosion in the proximity of the solar system. The expected number of events in JUNO is about 200 events for a SN in the Large Magellanic Cloud and about 5000 events considering a SN at the average possible distances of 10 kpc. The observation of these neutrino bursts allows a deeper understating of the explosion mechanism and time evolution to be obtained and the intrinsic properties of the neutrinos themselves to be probed. JUNO is also expected to play a central role in the next generation of multi-messenger astronomy. Finally, JUNO could be able to detect some events from the diffuse SN neutrino background, a low energy neutrinos flux produced by all past stellar core-collapse SN, improving the understanding of the average SN neutrinos signal and the underlying cosmology. The discovery potential is 3σ in 3 years of data taking and stringent constraints can be provided in case of non-observation. More detail about supernova neutrinos can be found in the collaboration paper [9].

3.5. *Geoneutrinos*

The surface heat flow of the Earth was established as 46(3) TW but the fraction that comes from primordial versus radioactive sources is not established yet. Since the matter is mostly transparent to neutrinos, by studying the geoneutrino flux it is possible to study the amount of radiogenic power produced in the depths of the Earth and have information about the relative abundance of uranium, thorium ad potassium, the naturally occurring radioactive nuclides. This information is also important for understanding the formation and evolution of the Earth. Within the first year of running, JUNO is expected to detect more geoneutrino events than all other detectors will have accumulated to that time, about 400 events per year. JUNO can measure the geoneutrino flux at the 8% precision level in 10 years of data taking by fixing the U/Th ratio, but it will be also able to provide precise measurement of the single U and Th components and their ratio. Since the detection channel is the IBD, the reactor antineutrinos events act as a background for the geoneutrino measurement, the knowledge of the reactor antineutrino spectrum is crucial and TAO will play an important role. In Figure 7 is shown the expected signal of geonetrinos compared to reactor ones.

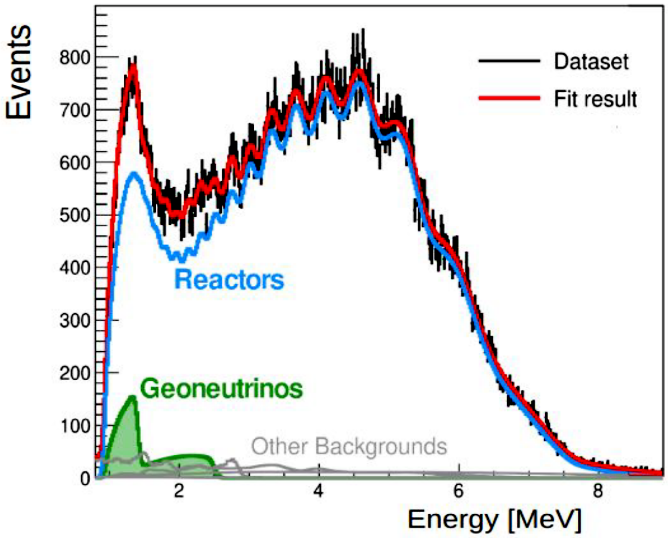


FIGURE 7: Geoneutrino and reactor neutrino spectra.

3.6. *Proton Decay*

With an unprecedented LS active volume, JUNO will be able to address many important topics beyond the standard model. One of the most promising is the search for proton decay in the channel $\mathrm{p} \rightarrow \mathrm{K}^{+} + \mu$. By exploiting a triple coincidence to suppress the background the JUNO expected sensitivity is 9.6×10^{33} y in 10 years of data taking. More details about proton decay can be found in the collaboration paper [10].

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