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Potential of core-collapse supernova neutrino detection at JUNO

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JUNO is an underground neutrino observatory under construction in Jiangmen, China. It uses 20kton liquid scintillator as target, which enables it to detect supernova burst neutrinos of a large statistics for the next galactic core-collapse supernova (CCSN) and also pre-supernova neutrinos from the nearby CCSN progenitors. All flavors of supernova burst neutrinos can be detected by JUNO via several interaction channels, including inverse beta decay, elastic scattering on electron and proton, interactions on ^{12}C nuclei, etc. This retains the possibility for JUNO to reconstruct the energy spectra of supernova burst neutrinos of all flavors. The real time monitoring systems based on FPGA and DAQ are under development in JUNO, which allow prompt alert and trigger-less data acquisition of CCSN events. The alert performances of both monitoring systems have been thoroughly studied using simulations. Moreover, once a CCSN is tagged, the system can give fast characterizations, such as directionality and light curve. This talk gives an overview of physics potential of CCSN neutrino detection in JUNO.

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1. Introduction

At the end of a massive star's whole life, it is believed to be able to collapse and explode to be a core-collapse supernova (CCSN). A CCSN can bring us various detectable signals, including electromagnetic signals, grativational waves and neutrinos. These will help us with the understanding of explosion mechanisms. So it is important to be prepared to observe these signals. As is described in [1], neutrino emission starts before core-collapse, which is called pre-supernova (pre-SN) neutrinos. The pre-SN neutrino emission starts as early as 10^{11}s before core-collapse and its luminosity increases as time approaches collapse. The SN neutrinos and gravitational waves usually lasts $O(10)$s, while the shock break out of electromagnetic signals are delayed by 10^5s. Also, the time information provided by CCSN neutrinos can improve the sensitivity of gracitational wave detection significantly. Hence, neutrino detection of both pre-SN neutrinos and SN neutrinos can serve as early warnings for CCSN.

Jiangmen Underground Neutrino Observatory (JUNO) [2], located in Jiangmen, China, is a multi-purpose neutrino experiment under construction. The main goal is to measure the neutrino mass ordering. It is designed to be a 20 kton liquid scintillator (LS) detector with 30 kton shielding water and will be the largest LS detetor in the near future. JUNO is equipped with about 18000 20-inch photomultiplier tubes (PMT) and 26000 3-inch PMTs. It is expected to reach 3%@1MeV energy resolution. Fig. 1 shows a schematic overview of the JUNO detector, which is taken from [3]. JUNO can detect CCSN neutrinos and provide early warning for CCSN.

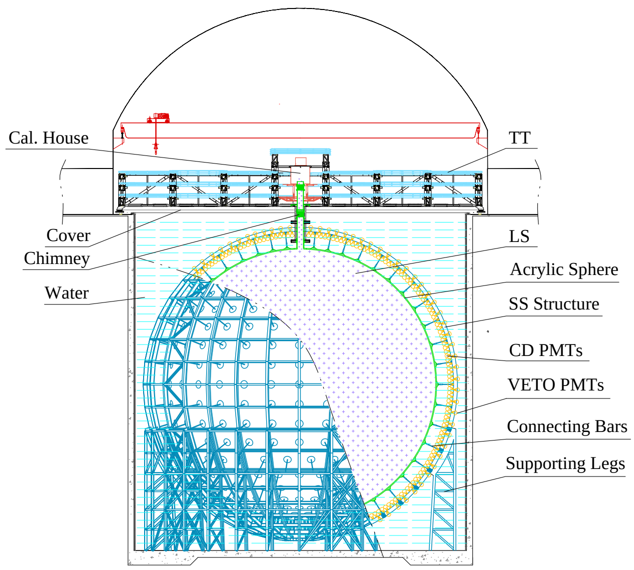

Figure 1: The schematic overview of JUNO detector.

2. Supernova neutrino detection at JUNO

Detecting supernova neutrino is also an important purpose of JUNO. It can see all flavors of neutrinos via several interactions. The main channels are inverse beta decay (IBD), $\bar{\nu}_e + p \to e^+ + n$, elastic scattering on electron (eES), $\nu + e^- \to \nu + e^-$ and elastic scattering on proton (pES), $\nu + p \to \nu + p$. JUNO is estimated to detect about 5000 IBDs, 300 eESs and 2000 pESs for CCSN at 10 kpc. Beyond these three main detection channels, JUNO can also detect supernova neutrinos through CC and NC interactions with ^{12}C nucleis (about 200 events and 300 events @10 kpc respectively). The visible energy spectra of all the flavors are shown in Fig. 2 [3].

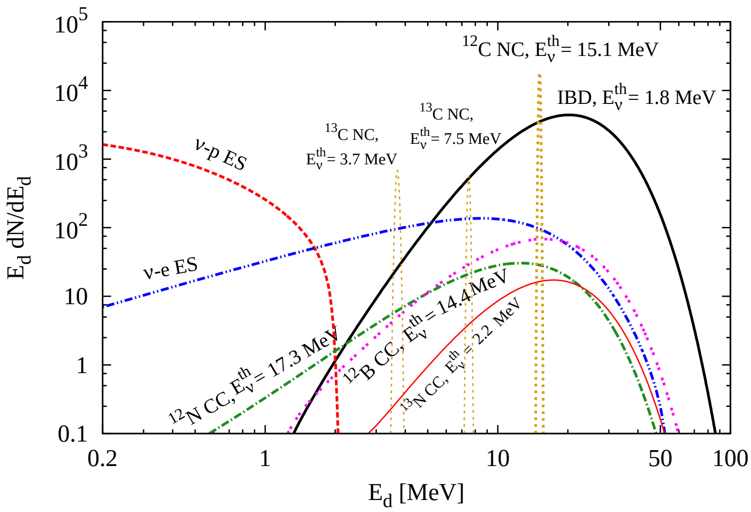

Figure 2: The visible energy spectra at JUNO detector for a typical SN at 10 kpc, where no neutrino flavor conversions are assumed and the average neutrino energies are $\langle E_{\nu_e} \rangle = 12MeV$, $\langle E_{\bar{\nu}_e} \rangle = 14MeV$ and $\langle E_{\nu_x} \rangle = 16MeV$.

3. Real-time supernova monitor systems at JUNO

Since when a CCSN happens, the signal rate will increase significantly, we can monitor whether a CCSN happens by monitoring the change of event rate. To provide early alerts for the next CCSN and record CCSN data as much as possible, a real-time CCSN monitor system is designed in JUNO. It is a redundancy design consisting of prompt monitor and online monitor. As is shown in Fig. 3, the prompt monitor is embedded in electronic trigger board which will have short time delay and can hence give fast alert on CCSN, while the online monitor is at the data acquisition (DAQ) stage which utilizes reconstructed information to maximize the monitoring ability. Once an alert is given, the internal collaborators and astronomical communities will be informed.

3.1 Prompt monitor

The prompt monitor is made up of two parts based on global trigger and multi-messenger (MM) trigger systems.

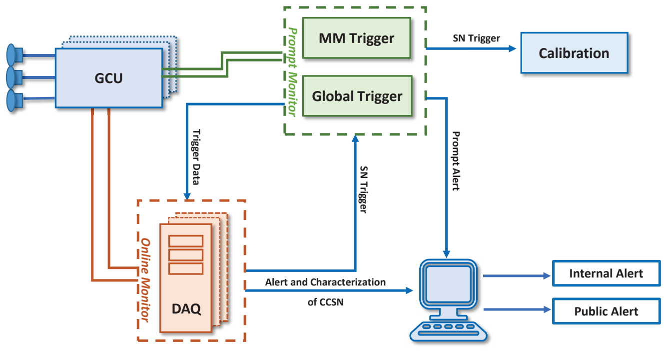

Figure 3: The design of JUNO CCSN monitor systems.

- **Based on global trigger**: The global trigger system is used to suppress the background events due to PMT dark noise coincidence and radioactivity of ^{14}C. It has an energy threshold of about 0.2 MeV. The monitor system based on global trigger is designed to monitor the rate of supernova neutrino candidates whose energy ranges from about 8 MeV to about 40MeV. It is on the same electronic board with global trigger. Based on the global triggered events, a quantity called N_{hit}, which is approximately proportional to energy, is used to select SN neutrino candidates. N_{hit} is calculated by counting the total number of pulses of all the PMTs. Fig. 4 shows the detector response of N_{hit} and the distribution of it from different sources. The dashed lines correspond to the selection criteria of SN candidates. As the figure shows, muons contribute a lot to the background. Hence, the water pool trigger available at the same electronic board as global trigger is applied to veto muon and its related backgrounds. It can reduce the background rate significantly.

- **Based on MM trigger**: MM trigger system is designed for low energy events. It will reduce the energy threshold to about 20 keV. To achieve this, fast filtering algorithms on FPGA is developed to reject dark noise. In the prompt monitor based on MM trigger, signals from all three main channels in JUNO are selected using techniques including pulse shape discrimination (PSD) to distinguish between proton and beta/gamma, electron and positron. Then the event rate can be monitored via algorithms such as Bayesian blocks.

Once an alert is found by prompt monitor system, it will be informed to DAQ and calibration system. The trigger-less T/Q data will be stored by DAQ and the calibration will be suspended.

3.2 Online monitor

The online monitor system at DAQ stage implemented in software utilize the reconstructed information to select candidates as in offline analysis. It has the potential to monitor pre-supernova neutrinos, so SN neutrinos and pre-SN neutrinos are monitored seperately. Online monitor uses the trigger-less T/Q data stream in DAQ, and a software trigger is performed to build events from the

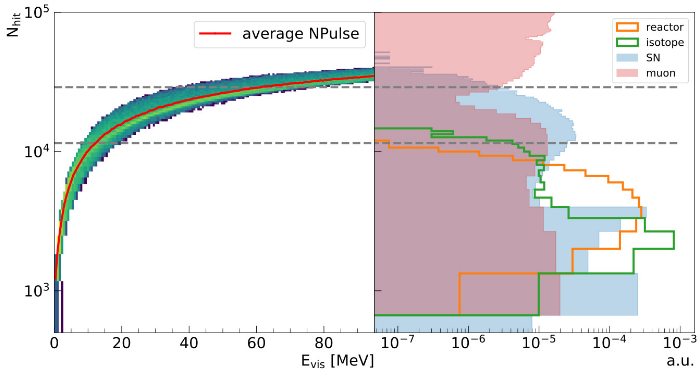

Figure 4: Left: the number of hits $N_{\rm hit}$ versus the visible energy for a global-triggered event. The red line is the average number of PMT hits with respect to visible energy. Positron samples with energy uniformly distributed from 0MeV to 100MeV is used. Right: the distribution of $N_{\rm hit}$ for different sources, including supernova neutrino, muon, reactor IBD and cosmogenic isotopes. The dashed lines incidate the criteria that are used for event selection.

trigger-less T/Q data. The vertex and energy information are extracted by reconstruction algorithms and used to select IBD events as SN candidates and pre-SN candidates. These candidates are monitored separately by SN monitor and pre-SN monitor. Three types of alert status are defined. An SN alert indicates an alert only from SN monitor, a pre-SN alert indicates an alert only from pre-SN monitor and a nearby alert indicates an alert from pre-SN monitor followed by an alert from SN monitor within 5 days.

Moreover, in order for fast characterization of CCSN, e.g direction, both SN and pre-SN candidates are stored for one week in the Event Accumulator. Once online monitor finds an alert, the direction of CCSN can be reconstructed using IBDs stored in the Event Accumulator using the formula: $\widehat{D} = \frac{1}{N}\sum_i \hat{X}^{(i)}_{pn}$, where $\hat{X}^{(i)}_{pn}$ is the unit vector between the vertex of positron and neutron [4]. JUNO may be able to detect O(100) pre-SN IBDs for a nearby pre-SN and hence has the potential to give pre-SN direction. For example, Ref. [5] shows JUNO has the potential to reconstruct the direction of pre-SN with the uncertainty of the reconstructed direction to be 70° at 68% confidence level for pre-SN at 0.2 kpc (with about 650 IBDs).

4. Energy spectrum unfolding

Through three main interaction channels, JUNO can detect all flavors of neutrinos and hence has the potential to reconstruct the energy spectra of all flavors. Here, works from [6] is used as an example for illustration. In this work, a model independent approach is proposed to extract the energy spectra of all flavors. The relationship between observed spectra of three main channels IBD, eES and pES and the flux of all flaovrs $\bar{\nu}_e$, ν_e and ν_x (x stands for μ and τ tyes) can be modeled simply by:$Ax = b$, where A is the response matrix reflecting the detector response and interaction cross section, x is the flux of three flaovrs and b is the observed spectra. In this linear form, unfolding method can be performed to extract the spectra of all flavors. Fig. 5 shows the unfolding result for SN at 10 kpc. The flux of $\bar{\nu}_e$ is mainly extracted from IBD events while the eES and pES provide the information for ν_e and ν_x. Note the unfolded flux of ν_e and ν_x at low energy is bad. This is due to the 0.2 MeV energy threshold at JUNO, which blinds the information from pES channel at low energy.

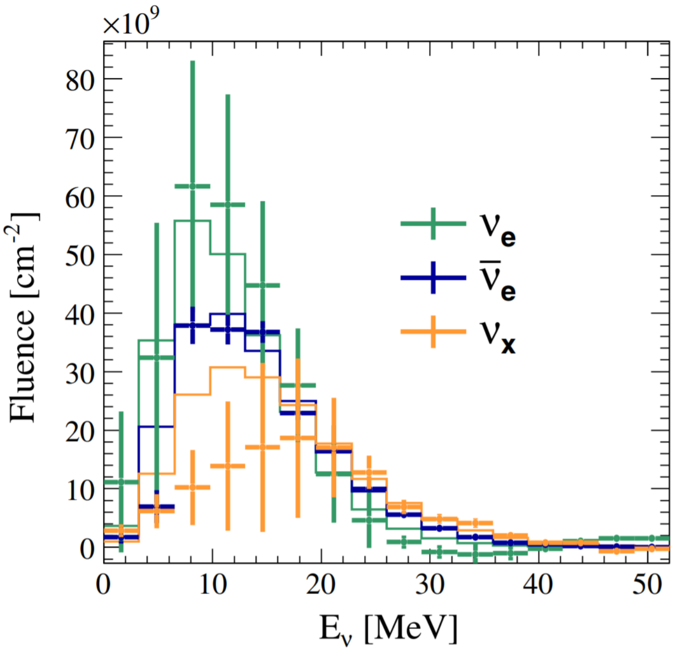

Figure 5: The unfolded energy spectra for a typical SN at 10 kpc, taken from [6] as an example.

5. Summary

As the largest LS detector in the near future, JUNO can detect all flaovrs of neutrinos through several interaction channels, which enables the potential for JUNO to provide spectral information of all flavors. To give alert to CCSN and store CCSN related data, a redundancy design of CCSN monitor systeim at JUNO is proposed which consists of both prompt monitor and online monitor. The prompt monitor can be based on global trigger or MM trigger to give fast alert on SN, while the online monitor utilizes reconstructed information to select IBD events both for SN and pre-SN. Also, the accumulated events in online monitor are able to give the direction of CCSN, both from SN IBDs and pre-SN IBDs.

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