PROCEEDINGS OF SCIENCE

Extending JUNO's Astrophysical Reach with a Low-Energy Multi-Messenger Trigger System

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The Jiangmen Underground Neutrino Observatory (JUNO) will be a 20kton liquid scintillator detector, currently under construction in southern China. JUNO will be instrumented with close to 18,000 20-inch photomultiplier tubes (PMTs), possessing the highest photocathode coverage of any kiloton-scale liquid scintillator or Cherenkov detector to date. With its first-rate size, PMT coverage and low-background levels, JUNO will have highly competitive sensitivity to extra-terrestrial MeV-scale neutrinos. To maximise its astrophysical potential, a dedicated multi-messenger (MM) trigger has been developed. The new system will allow for an unprecedented minimum energy threshold of O(10keV), monitoring an extensive energy band of all-flavour neutrinos. The MM trigger will rapidly remove PMT dark noise, filter 14C background events and search in real-time for transient neutrino signals. Upon the detection of an astrophysical neutrino burst, JUNO can communicate with global multi-messenger facilities on a millisecond time scale, allowing for rapid follow-up measurement campaigns across the various detectors.

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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) experiment, aims to measure to an unprecedented level of precision, neutrino oscillation in the antineutrino energy spectrum from nearby nuclear reactors. In doing so, JUNO's target is to demonstrate if the neutrino mass ordering and measure neutrino oscillation parameters to a sub-percent level of precision [1]. JUNO (Figure 1) will be instrumented with close to 18,000 20-inch PMTs and 25,600 3-inch PMTs, watching 20 kilotons of liquid scintillator, expected to achieve the highest photocathode coverage of any kiloton-scale liquid scintillator or Cherenkov detector to date. This level of light collection will enable the detector to have the excellent energy resolution needed to resolve the fine oscillation structure of the reactor antineutrino energy spectrum, as well as yielding a very low minimum energy threshold.

Another major target for JUNO is the detection of astrophysical neutrinos. Following the single instance of supernova (SN) neutrino measurements in 1987 [2], made up of 24 SN antineutrino candidate events, several detectors have joined the SuperNova Early Warning System (SNEWS) [3], as part of the rapidly growing field of Multi-Messenger (MM) astronomy. A burst of neutrino events is expected to arrive to Earth hours prior to the detection of any photons from a core-collapse SN. Coincident measurements of this neutrino burst across multiple detectors increases the confidence in the warning sent out to other electromagnetic, gravitational wave and cosmic ray detectors around the world, each attempting to observe the imminent SN event.

The only measurement of SN neutrinos, the basis of hundreds of publications, occurred through the primary channel of inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$, which JUNO will be highly proficient at tagging. However, JUNO will have a unique ability push to a brand new low energy threshold, while also notably measuring all neutrino flavours, through the elastic neutrino-proton scattering channel $\nu_x + p \rightarrow \nu_x + p$. These events are typically unobservable in current kton liquid scintillators, due to their low energies. Measuring all neutrino flavours gives an important handle on the total energy emission of SN event, applying time constraints on potential SN evolution mechanisms, hinting at the origin of cosmic rays, black hole formation, as well as probing any flavour conversions that may occur.

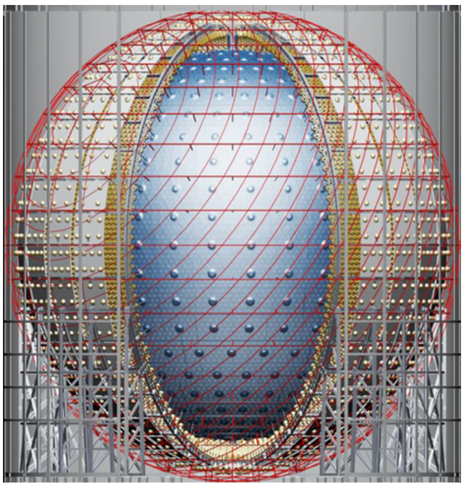

Figure 1: Schematic of the JUNO detector.

2. Multi-Messenger Trigger

JUNO's primary 'global' trigger expects the detector to reach a minimum energy threshold of ~0.2 MeV [4]. In order to maximise JUNO's energy range and astrophysical potential, a separate 'Multi-Messenger' (MM) trigger system, will be installed at JUNO's site. The trigger aims to allow for an unprecedented low energy threshold of 20keV. The primary role of the MM trigger processing unit shown in figure 2, is to separate neutrino physics events from the large rates of PMT dark noise (where each 20-inch PMT in JUNO expects dark noise rates of O(10kHz). To achieve this, a number of likelihood and machine-learning algorithms are being developed, written directly on powerful the FPGAs in the MM trigger processing unit. FPGA-run algorithms are needed to ensure sufficient speeds sifting through the massive amounts of PMT noise and low-energy data. The aim of the Multi-messenger trigger system is to enable the detection of low-energy (predominantly transient) neutrino signals. With this, the trigger intends to boost JUNO's ability to rapidly declare potential SN events to the global network of optical, gravitational and neutrino detectors.

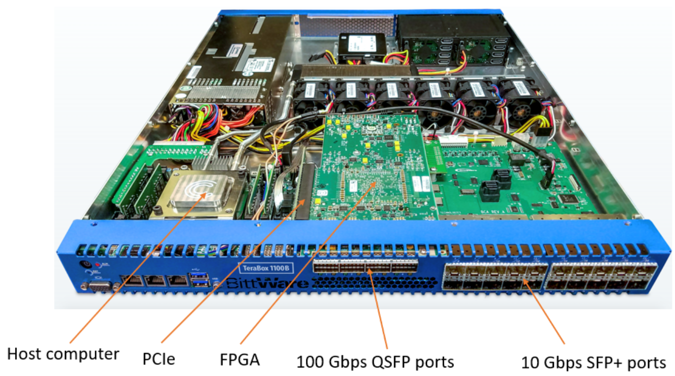

Figure 2: The Multi-messenger trigger system processing unit, containing TeraBox 1100L FPGA system, needed to run the rapid dark noise removal algorithms.

3. Expected Performance

Parallel to the hardware developments for the MM trigger hardware systems, an equivalent system was developed in JUNO's Geant4-based detailed simulation system, SNiPER [5]. This allowed for the development and testing of MM trigger algorithms in simulation. Figure 3 shows the expected performance of the MM trigger's primary dark noise removal likelihood method. Shown is the trigger efficiency a function of electron kinetic energy, for electrons generated throughout the liquid scintillator within JUNO's acrylic vessel. It can be seen that a trigger efficiency of ~ 40% is expected at 20keV, where the algorithm is expected to remove ~99.9% of triggered events due to random coincident PMT dark noise. Further developments are underway to attempt further removal of triggered events due to non-neutrino signal events such as naturally occurring ^{14}C β-decay within the detector and Cherenkov photons due to the irreducible radioactivity on PMT glass.

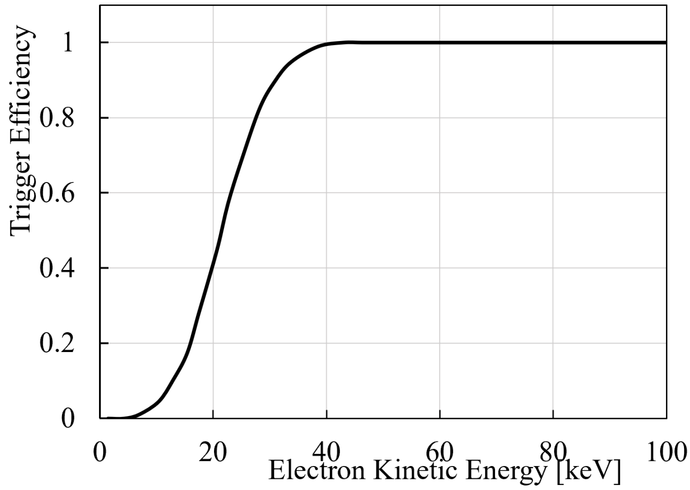

Figure 3: MM trigger efficiency for simulated electron events in the JUNO detector as a function of electron kinetic energy.

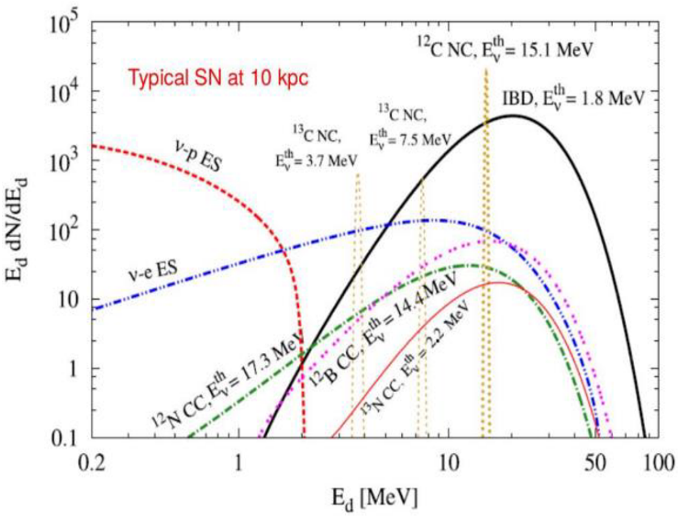

Figure 4: The expected visible energy spectra for the various detection channels observable at JUNO for a typical CCSN occurring 10kpc from Earth. Plot taken from [4].

3.1 Boosting Supernova Detection efficiency

The upgrade to SNEWS, SNEWS 2.0 [3] aims to maximise sensitivity to future to supernova events by adapting the focus of their system to focus on maximising information extraction from signal bursts, instead of maximising purity. Detectors joining the SNEWS 2.0 system will ideally have good sensitivity to neutrino bursts, have minimal alert latency and well as the implementation of potential alerts for pre-supernova neutrinos.

Seen in figure 4, are inverse beta decay (IBD) events due to $\bar{\nu}_e$ events. IBDs are the golden channel used to detect SN bursts, with JUNO tailored to be efficiency to detect IBDs, their high energies, low backgrounds and high interaction rate in the detector. The MM trigger can be used to add to this, boosting sensitivity to the low energy channels, predominantly through proton elastic scattering, and possibly having sensitivity to ^{12}C through coherent elastic neutrino nucleus scattering. Unlike the IBD channel, the elastic scattering channels occur for neutrinos of all flavours, with proton elastic scattering signal event rates expected to be of a similar order of magnitude to the IBD channel. While event rates can be high, background rates are extensively higher for these singles events compared to IBDs, particularly at the lowest energies due to ^{14}C β decays, which have a Q-value of $\sim$ 156keV. While this limits the boost in sensitivity that the MM trigger could provide, benefit may be gained due to typical SN models predicting earlier arrivals for ν_e events, as shown in figure 5 compared to their antiparticle counterparts. This means if the burst due to lower energy ν_x events is detected by the MM trigger, earlier SN signals may be declared, minimising the alert latency for JUNO, an important factor to be a contributing member to SNEWS, which JUNO aims to join once operational.

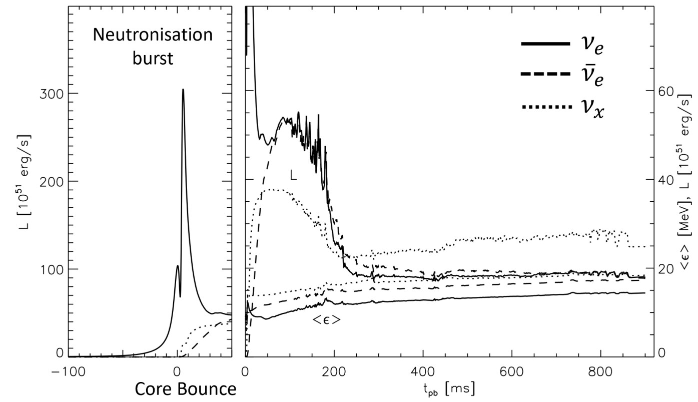

Figure 5: Luminosity evolution of neutrinos from a simulated 15 solar mass CCSN. This figure was adapted from [6].

References

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