# JUNO: a General Purpose Experiment for Neutrino Physics Postprint

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## Abstract

JUNO is a 20 kt Liquid Scintillator Antineutrino Detector currently under construction in the south of China. This report reviews JUNO's physics programme related to all neutrino sources but reactor antineutrinos, namely neutrinos from supernova burst, solar neutrinos and geoneutrinos.

## Full Text

## Preamble

**JUNO: A General Purpose Experiment for Neutrino Physics**

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*On behalf of the JUNO Collaboration*

JUNO is a 20 kt liquid scintillator antineutrino detector currently under construction in southern China. This poster reviews JUNO' s physics programme related to all neutrino sources except reactor antineutrinos, namely neutrinos from supernova bursts, solar neutrinos, and geoneutrinos.

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## 1. Introduction

JUNO is a Liquid Scintillator Antineutrino Detector (LAND) currently under construction in southern China (Jiangmen city, Guangdong province). Once completed, it will be the largest LAND ever built, consisting of a 20 kt target mass of linear alkyl-benzene (LAB) liquid scintillator monitored by approximately 18,000 twenty-inch high-quantum-efficiency photomultiplier tubes providing ~80% photocoverage. Large photocoverage and high quantum efficiency are pivotal parameters that enable an unprecedented 3% energy resolution at 1 MeV. The conceptual design report [1] foresees the liquid scintillator contained in an acrylic sphere 12 cm thick and 36 m in diameter, immersed in a cylindrical water pool that serves both as a shield against environmental radioactivity and as a Cherenkov detector for tagging and vetoing cosmic muons.

Achieving the target energy resolution requires ultimate control over calorimetry systematics with minimal impact. For this reason, a novel LAND design incorporates a second layer of small PMTs to provide complementary calorimetric information with an independent systematic budget, enabling a combined, more precise and accurate energy scale determination. This calorimetry redundancy system remains under optimization for JUNO' s physics programme. While JUNO' s primary physics goal is to determine the neutrino mass hierarchy by detecting reactor $\bar{\nu}_e$ from two nuclear power plants located 53 km from the detector, this poster focuses on JUNO' s physics programme utilizing all neutrino sources *except* reactors: supernova neutrinos, solar neutrinos, and geoneutrinos. A complete review of JUNO' s physics goals can be found in [2].

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## 2. Neutrino Physics at JUNO

### Supernova Burst Neutrinos

A supernova is a stellar explosion that briefly outshines an entire galaxy, radiating as much energy as the Sun or any ordinary star emits over its entire lifespan. During such an explosion, 99% of the gravitational binding energy of the newly formed neutron star is emitted as neutrinos. Observation of supernova neutrinos is expected to play a crucial role in both particle physics and astrophysics.

Here we focus on the astrophysical aspects, where a supernova signal could help answer several fundamental questions: (I) What are the conditions inside massive stars during their evolution? (II) What mechanism triggers the supernova explosion? (III) Are supernova explosions responsible for producing heavy chemical elements? (IV) Is the compact remnant a neutron star or a black hole? Each question deserves dedicated discussion, but limited space permits only case (I) as an example.

The Standard Stellar Evolution Model describes stellar temperature and density as functions of time and distance from the center. Optical observations provide benchmark data for testing this model but have limited power to constrain the innermost layers, as high stellar density causes optical photons to propagate mainly via diffusion, losing all information about the core. In contrast, neutrinos interact only weakly with matter and represent a powerful probe of stellar interiors. For a star approaching collapse, neutrino production is dominated by thermal processes (mainly $e^+e^-$ annihilation into $\nu\bar{\nu}$ pairs), causing both the neutrino production rate and mean energy to increase significantly with temperature. Consequently, the final stages of nuclear burning produce the most abundant neutrino signal (called pre-supernova neutrinos), which is easier to detect and powerful for constraining stellar evolution.

Fig. 1 [Figure 1: see original paper] shows the simulated inverse beta decay (IBD) event rate in JUNO for the nearest possible supernova progenitor (the red supergiant Betelgeuse), assuming a mass of 20 solar masses ($M_\odot$) at a distance of 0.2 kpc. The sudden rate drop approximately 0.6 days before explosion is attributable to a core temperature decrease, primarily due to silicon depletion in the core. For an actual supernova explosion, JUNO's ability to precisely measure the position of this dip could discriminate between different progenitor masses. Moreover, the rapid rise beginning a few hours before core collapse makes JUNO the ultimate early-warning system for supernova explosions, providing extremely valuable information to the astrophysics community.

For a typical galactic supernova at 10 kpc, more than 5000 signal events are expected from the IBD channel alone. Several other neutrino interactions also contribute to the total event rate, differing in yield, energy spectrum, and threshold. Fig. 2 [Figure 2: see original paper] shows all contributions together, where $E_d$ is the deposited visible energy, $E_{th}$ is the energy threshold for each process, $\nu$-$p$ denotes neutral current interactions on protons, $\nu$-$e$ denotes elastic scattering on electrons, $^{12}$C NC denotes neutral-current-mediated carbon excitations, $^{12}$N CC denotes charged-current $\nu_e$ interactions on $^{12}$C, and $^{12}$B CC denotes the analogous charged-current interactions initiated by $\bar{\nu}_e$.

## Solar Neutrinos

The Sun is a powerful source of $\nu_e$ with $\mathcal{O}(1\,\text{MeV})$ energy, produced by thermonuclear fusion reactions in the solar core. JUNO' s solar neutrino programme focuses on neutrinos from the $^7$Be and $^8$B chains. Despite great achievements in recent decades, important aspects of solar neutrino physics remain to be clarified, with several questions of great relevance for astrophysics and particle physics awaiting definitive answers. Two of the most important are: (I) resolution of the solar metallicity problem, and (II) detailed analysis of the oscillation probability' s energy dependence at the low-energy end of the $^8$B neutrino spectrum.

(I) The solar metallicity problem emerged when the former agreement between the Standard Solar Model (SSM) and solar data was compromised by revision of the solar surface heavy element content, creating a discrepancy between SSM predictions and helioseismology results. Different SSM versions predict different $^8$B and $^7$Be neutrino fluxes. JUNO' s capability to determine these fluxes with high accuracy, combined with future CNO flux measurements from other experiments, could help resolve this key issue in nuclear astrophysics.

(II) According to the Mikheyev-Smirnov-Wolfenstein (MSW) effect, neutrino oscillation parameters differ depending on whether neutrinos propagate through matter or vacuum. For solar $\nu_e$, the transition between these regimes occurs in the 1-3 MeV range, making $^8$B solar neutrinos—with their continuous spectrum extending far beyond 3 MeV—a privileged tool for studying MSW-modulated energy dependence. Theory predicts a smooth transition between vacuum and matter-related $\nu_e$ survival probabilities, manifesting as an up-turn in the spectrum. However, no existing experiment has observed clear evidence of this effect except Super-Kamiokande, which obtained mild evidence [3]. JUNO' s capability to perform an independent, high-significance test of this up-turn would be extremely important for confirming the consistency of the standard LMA-MSW solution or revealing possible deviations.

The challenge in detecting solar $\nu_e$ at JUNO is that they are observed only via elastic scattering, producing an experimental signature (single energy deposition) indistinguishable from most backgrounds. The two main background sources are natural radioactivity and cosmogenic isotopes. The former must be suppressed through high radiopurity in all detector components. JUNO' s baseline radiopurity scheme targets residual contamination levels of $10^{-16}$ g/g for $^{232}$Th, $10^{-16}$ g/g for $^{40}$K, and $10^{-17}$ g/g for $^{14}$C. This matches levels achieved during KamLAND' s solar phase and would yield a signal-to-background ratio of 1/3. A more demanding "ideal" radiopurity scheme improves these levels by one order of magnitude, corresponding to Borexino Phase I and enabling a 2/1 signal-to-background ratio. Fig. 3 [Figure 3: see original paper] shows the radioactive background energy spectra for the ideal radiopurity scenario together with the $^7$Be neutrino signal.

Among cosmogenic isotopes, the most problematic are long-lived isotopes—$^{10}$C ($\tau = 24.4$ min), $^{11}$C ($\tau = 27.8$ s), and $^{11}$Be ($\tau = 19.9$ s)—since they cannot be suppressed by muon veto without introducing significant dead time. Fig. 4 [Figure 4: see original paper] shows the energy spectra of these background events. The only viable strategy is to tag them via three-fold coincidence (muon + spallation neutron + isotope decay) and subtract them statistically from the total spectrum.

## Geoneutrinos

Over the last half-century, Earth' s surface heat flow has been established to be $46 \pm 3$ TW, yet the community vigorously debates what fraction originates from primordial versus radioactive sources. This debate touches on Earth' s composition, chemical layering in the mantle, the nature of mantle convection, the energy driving plate tectonics, and the power source of the geodynamo that generates the magnetosphere shielding Earth from harmful cosmic rays. Radioactive beta decays of heavy elements (such as Th and U) within Earth produce an upward $\bar{\nu}_e$ flux (geoneutrinos) detectable at JUNO via IBD reactions. Precise measurement of this flux would constrain the absolute abundance of Th and U in Earth, enabling: (I) characterization of the chondritic meteorites that formed Earth, (II) discrimination among parameterized mantle convection models describing Earth’ s thermal evolution, (III) potential identification and characterization of deep, hidden mantle reservoirs, and (IV) determination of the radiogenic contribution to terrestrial heat flow. Such studies can also place stringent limits on the power of any natural nuclear reactor in or near Earth’ s core.

The main experimental challenge in detecting geoneutrinos is disentangling them from the overwhelming reactor $\bar{\nu}_e$ signal. This separation can only be achieved through statistical subtraction, relying heavily on precise modeling of the low-energy reactor $\bar{\nu}_e$ spectrum. Moreover, interpreting the geoneutrino signal in terms of mantle radioactivity requires subtracting the Earth's crust contribution, as the crust surrounding the detector is known to dominate the total geoneutrino budget. Therefore, detailed geological, geochemical, and geophysical studies of the regions surrounding the detector are essential for understanding the relative crust and mantle contributions to the geoneutrino signal at JUNO.

## 3. Conclusion

JUNO’ s physics programme is extremely broad, making it a genuine general-purpose neutrino experiment. This poster has presented only some topics associated with non-reactor neutrinos, namely supernova neutrinos, solar neutrinos, and geoneutrinos. A complete review of JUNO’ s physics programme can be found in [2].

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## References

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*Note: Figure translations are in progress. See original paper for figures.*