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JUNO potential in non-oscillation physics

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The Jiangmen Underground Neutrino Observatory (JUNO) is a next-generation liquid scintillator experiment being built in the Guangdong province in China. JUNO's target mass of 20 kton will be contained in a 35.4 m acrylic vessel, itself submerged in a water pool, under about 700 m of granite overburden. Surrounding the acrylic vessel are 17612 20" PMTs and 25600 3" PMTs. The main goal of JUNO, whose construction is scheduled for completion in 2022, is a 3-4σ determination of the neutrino mass ordering (MO) using reactor neutrinos within six years, as well as a precise measurement of θ_{12}, Δm^2_{21}, and Δm^2_{31}. JUNO's large target mass, low background, and dual calorimetry, leading to an excellent energy resolution and low threshold, allows for a rich physics program with many applications in neutrino physics. The large target mass will allow for high-statistics solar-, geo-, and atmospheric neutrino measurements. JUNO will also be able to measure neutrinos from galactic core-collapse supernovae, detecting about 10,000 events for a supernova at 10 kpc, and achieve a 3σ discovery of the diffuse supernova neutrino background in ten years. It can also study non-standard interactions e.g. proton decay, indirect dark matter searches, and probe for Lorentz invariance violations. This paper covers this extensive range of non-oscillation topics on which JUNO will be able to shed light.

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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a next-generation liquid scintillator experiment currently being built in the Guangdong province in China [1]. The main goal of JUNO, whose construction is scheduled for completion in 2022, is a 3-4σ determination of the neutrino mass ordering (MO) using reactor neutrinos within six years, as well as a precise measurement of θ_{12}, Δm^2_{21}, and Δm^2_{31}. While the accomplishment of these (and other) goals and their ramifications are described in details in ref. [1], this paper focuses on the multitude of non-oscillation-related physics topics that JUNO will be able to shed light on in the competitive landscape of experimental particle physics. After a description of the JUNO detector in section 2, section 3 will give details on the detection of solar neutrinos, geo-neutrinos, atmospheric neutrinos, neutrino as a tool to detect core-collapse supernovæas well as to possibly discover a diffuse supernova neutrino background, multi-messenger astronomy with JUNO, and exotic searches.

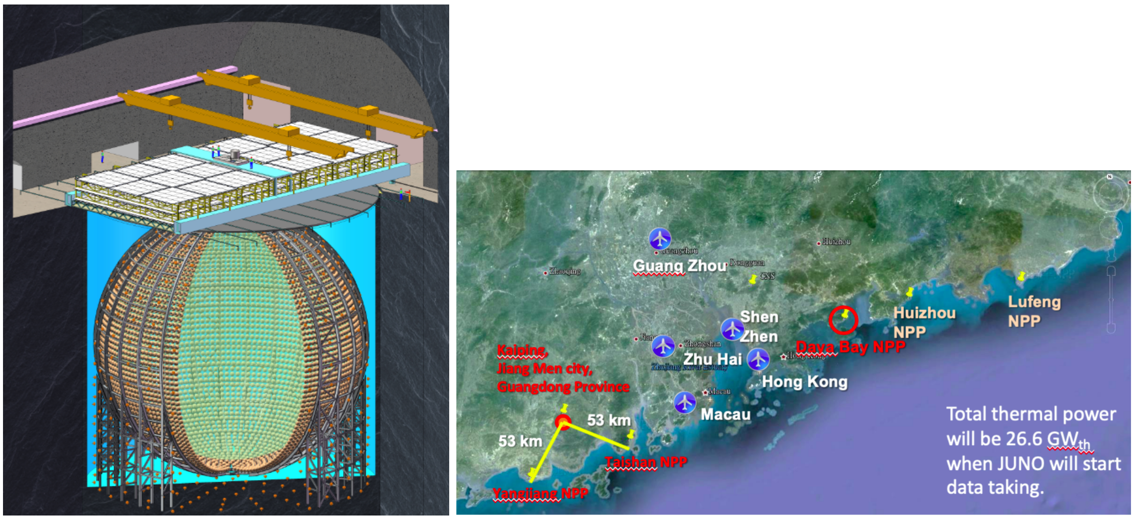
2. The JUNO detector

The JUNO detector, see fig. 1, is currently under construction in the Guangdong province in China. As the largest liquid scintillator (LS) detector ever built, it will contain 20 kt of LS in a 35.4 m acrylic sphere in the so-called *central detector* (CD). The acrylic sphere is contained in a cylindrical tank containing ultra-pure water as well as veto photomultiplier tubes (PMTs). Above the tank, a top muon veto called the *top tracker* (TT), made of plastic scintillator strips, will be built as well.
JUNO will use a total 17612 large 20" PMTs and 25600 small 3" PMTs. This allows a coverage of about 75+3%, respectively, with the small PMTs placed in the gaps between the large ones. Additionally, by comparing energy estimators from the large PMT and small PMT systems, this allows one to reduce sources of systematics related to photo-detection.
Through its high light yield of 1345 p.e./MeV, the JUNO liquid scintillator and detector are designed to reach an unprecedented 3% energy resolution at 1 MeV. A thorough calibration campaign will also allow JUNO to reach a less than one percent uncertainty on its energy scale.
A satellite experiment for JUNO: the Taishan-Antineutrino-Observatory (TAO) is being built at a distance of 30 m from the Taishan nuclear power plant. It will be operated with a Gd-doped scintillator held at −50 °C with silicon photomultipliers (SiPMs) reaching a 99% coverage to measure the unoscillated neutrino spectrum with a 1.7% energy resolution at 1 MeV. This will provide a model-independent reference spectrum for JUNO and cancel systematics in the reactor spectral shape. More relevant for this paper, it will also precisely measure said shape to test it for new physics and to allow for a better understanding of the neutrino reactor anomaly at 5 MeV.

3. Non-oscillation physics

3.1 Solar neutrinos

This section firstly focuses on JUNO's capabilities to detect solar neutrinos in the energy range spanning from 0.3 MeV to 2.1 MeV using elastic scattering off electrons. This range includes prominent signatures of solar neutrinos, including the Compton-like edge of recoiled electrons from the mono-energetic so-called ^{7}Be neutrinos and pp-neutrinos in the lower energy regions. The main



(a) (b)

Figure 1: (a) a 3D representation of the JUNO detector. One can see the 35.4 m acrylic sphere containing the LS and surrounded by PMTs. More PMTs can be seen in the water volume around the central detector, as well as the top tracker. (b) the location of JUNO as compared to known landmarks. The detector is at the red dot - equidistant at 53 km from the Taishan and Yangjiang nuclear power plants.

advantages of JUNO, compared to previous LS neutrino experiments that have performed precise solar neutrino measurements [2, 3], are its extremely large fiducial mass and its unprecedented energy resolution. Based on these facts, JUNO has the potential to provide world-leading precision on the rates of ^{7}Be and pp-neutrinos in less than a year, but these results are strongly dependent on internal radioactivity.

The most important background is that of the ^{238}U and ^{232}Th chains, detectable via fast $^{214(212)}$Bi-$^{214(212)}$Po coincidences, whose levels should be kept below 1×10^{-16} g g^{-1} [1] to allow for meaningful measurements.

Achieving a more precise measurement of ^{7}Be and pp neutrinos than the current existing ones would go towards solving the long-standing metallicity problem, study the MSW transition region, and study non-standard interactions [1]. The detection of other kinds of solar neutrinos also strongly depends on the possibility of tagging ^{11}C cosmogenic background, with the exception of ^{8}B and hep neutrinos which are addressed in the next section.

Secondly, in the energy range from about 2 MeV to 20 MeV, above the influence of ^{11}C backgrounds, elastic scattering off electrons can also be used to detect ^{8}B neutrinos [4]. While in theory hep-neutrinos should also be present in that range, their rate is too small to detect, at least with JUNO. The remaining backgrounds are from reactor neutrinos whose rate declines rapidly with rising energy, cosmogenic isotopes that can be tagged with smart cylindrical cuts around muons, gamma rays from externals which can be removed with fiducial volume cuts, and internal radioactivity.

Additional detection channels are possible in the CC and NC interactions between neutrinos and carbon nuclei. The addition of those interactions with ^{13}C in particular could add about 9000 signal events to the sample over the ten year measurements, but more detailed studies are ongoing.

Assuming an internal contamination of 1×10^{-17} g g^{-1} [1] for ^{232}Th and ^{238}U, we expect a total of about 60000 ES signal events and 30000 background events in ten years of data-taking. This large sample can be used to observe a possible upturn in the MSW transition region with a significance of about 3σ. Additionally, we can expect to improve existing measurements of the day-night asymmetry and explore the light tension between Δm^2_{21} from solar and reactor neutrinos, all in the same experiment. The flux measurement can also help with the solar metallicity problem.

3.2 Geo-neutrinos

Geo-neutrinos are neutrinos from the radioactive decay of long-lived isotopes lodged inside the Earth's mantle and crust. These isotopes are remnants carrying information about Earth's formation. Geo-neutrinos are exclusively detected via inverse-beta-decay (IBD) of anti-electron-neutrinos from the ^{238}U and ^{232}Th chains. Theoretically the geo-neutrino-producing isotope ^{40}K also exists, but it is not detectable above the 1.8 MeV threshold innate to IBD interactions. In JUNO we expect about 400 events per year (or about 40 TNU), which would result in an uncertainty of about five percent in six years of data-taking [1]. To put this sample in the global context, the two other experiments that have previously measured geo-neutrinos are KamLAND and Borexino, who respectively measured about 169 neutrinos in six years and 53 in nine [5, 6].
Local geological studies are ongoing near the JUNO site, using seismographic stations, deep seismic soundings to study gravitational anomalies to get information about the local crust. This is the most important source of systematic uncertainties as although JUNO is sensitive to neutrinos from the entire planet, about half of the signal events are expected to origin from decays within a 500 km radius from the experiment. The geo-neutrino measurement of JUNO can be used to study the radiogenic contribution to the terrestrial heat production. Most importantly JUNO will be sensitive to the Th/U mass ratio which is an important parameter to understand Earth's formation.

3.3 Atmospheric neutrinos

Atmospheric neutrinos are a very particular natural source of neutrinos since they consist of neutrinos from all flavours, with a very large baseline and energy range. They can also be used to probe the MSW effect which in the case of JUNO can offer a small but complementary sensitivity to the MO measurement [1]. JUNO's large target mass and unprecedented energy resolution can offer a lot of information about atmospheric neutrinos, including some directional information despite the isotropic nature of scintillation light emission.
More specifically, it was shown that JUNO can use time information [7] in order to discriminate between ν_e and ν_μ neutrinos. This mainly comes from the fact that ν_μ-induced tracks have a broader time profile than the purely leptonic ν_e events. The broadness of NC interactions are usually somewhere between the two aforementioned CC interactions and cannot be told apart so easily. Studies indicate that JUNO will be able to reconstruct the atmospheric neutrino spectrum with a high precision from 0.1 GeV to 10 GeV, and give a low ($< 2\sigma$) sensitivity to $\sin^2\theta_{23}$ and δ_{CP}. It is to be noted that this would constitute the first sub-GeV atmospheric neutrino measurement with a liquid scintillator detector.

3.4 Core-collapse supernovæ

Core-collapse supernovæare expected to happen once every 30 to 100 years. This implies an up to 28% probability for at least one to happen during the ten years of JUNO's planned detector

operations. The following section focuses on the expected signal and physics from a typical expected core-collapse supernova at a nominal distance of 10 kpc.
JUNO can detect all flavours of the $O(10\,\mathrm{MeV})$ post-shock neutrinos [1]. The main detection channels for JUNO are from IBD and ES off protons and electrons. However CC and NC neutrino-^{12}C interactions are also expected to play a role, as well as subsequent (coincident) decays from ^{12}B, and ^{13}N albeit to a lesser extent. In the first 10 s following the first supernova neutrino event, JUNO is expected to detect 5000 neutrinos from IBD, as well as 2000 νpES, 300 νeES and 500 ν^{12}C events. This is made possible through a dedicated trigger scheme with a 100 keV threshold, operating in parallel to the main JUNO so-called "global trigger".
Following the previous assumptions, a typical 10 kpc would enable JUNO to measure the flavour content, time evolution, flux, and energy spectrum of supernova neutrinos. This would allow us to study star parameters, supernova physics in general, as well as lead to a better understanding of late-stage stellar evolution. The timing information would also lead to an expected constraint of $m_\nu < (0.83 \pm 0.24)$ eV (95% CL) on the absolute neutrino mass [8].

3.5 Diffuse supernova neutrino background

While Core-collapse supernovæare cataclysmic events known to produce enormous amounts of neutrinos in a short span of time, they are very rare events in a single galaxy. However neutrinos can travel between galaxies and as such the total integrated flux of neutrinos from past supernovæ in the visible universe can be calculated to be on the level of $10\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [1]. This is called the "Diffuse supernova neutrino background" or DSNB for short. This result of course depends on several assumptions, including but not limited to the fraction of black hole formation in core-collapse supernovæ and the average SN neutrino spectrum. Depending on the model, JUNO is expected to measure up to four DNSB events per year in the IBD detection channel, in the energy range above that of reactor neutrinos.
The main background stems from NC $\nu^{12}C$ interactions with atmospheric neutrinos. While the signal is very low, even for a large detector such as JUNO, the delayed signal from the neutron capture and the pulse shape discrimination (PSD) power of liquid scintillator were calculated to, under reasonable assumptions, lead to a 3σ discovery power in ten years of measurement should the mean anti-electron-neutrino energy be above 15 MeV. In fact, after the PSD cut, the DSNB signal is expected to dominate above the reactor neutrino range and up to about 22 MeV.

3.6 Multi-messenger astronomy

Additionally to the dedicated supernova trigger system described in the previous section, a multi-messenger trigger is currently under development. This system is designed to help JUNO reach an energy threshold of $O(10\,\mathrm{keV})$, using FPGA for fast event classification with real-time reconstructed time and charge (so called T-Q pairs) information. This system will make it possible for JUNO to observe broadband transient events. As such, JUNO is expected to become a large player in the SNEWS2.0 [9] system for multi-messenger astronomy.

3.7 Exotic searches and new physics

Nucleon decay has long been one of the most prominent markers of grand unified theories (GUT). JUNO is expected to reach competitive levels with a sensitivity of 8.34×10^{33} yr (90% CL) in ten

years of data-taking. This is made possible through a triple coincidence search in the $p \to K^+ + \nu$ channel which continues with $\bar{\nu}K^+ \to \mu^+ + \nu_\mu; \mu^+ \to e^+ + \nu_e + \bar{\nu_\mu}$. This is a significant advantage of liquid scintillator detection over e.g. water-Cherenkov methods. Other nucleon decay modes such as the supersymmetry-favoured $p \to \pi^0 + e^+$, as well as the $n \to 3\nu$ and $p \to \mu^+\mu^+\mu^-$ channels are under investigation [1].
JUNO can also be expected to give competitive limits on spin-dependent dark-matter (DM)-nucleon interaction cross-sections in the cold-DM energy ranges below 20 GeV. This is achievable in the $\chi\chi \to \nu\bar{\nu}$ and $\chi\chi \to \tau^+\tau^-$ channels, reaching down to the level of 1×10^{-40} cm^2 to 1×10^{-39} cm^2. JUNO is also expected to improve current limits (from SuperK) on putative primordial black holes in the mass range of 1×10^{15} g to 1×10^{16} g by an order of magnitude by looking at anti-neutrinos. The JUNO detector will be able to address and shed light on numerous topics possibly going beyond the standard model, or at the very least probing currently existing limits. Firstly staying in the topic of purely neutrino physics, JUNO will test the neutrino reactor anomaly with its satellite experiment TAO (see section 2) which will perform a high-precision of the reactor neutrino spectrum in the entire anomalous range. With its very short baseline TAO will also provide leading limits on light sterile neutrinos in a Δm^2 range around the eV scale, as well as general limits on physics beyond the standard three neutrino framework. Additionally, JUNO is expected to give limits on Lorentz invariance violation by probing sidereal modulations of the measured reactor anti-neutrino rates and give competitive limits on nuclearites in the mass range from 1×10^{13} GeV to 1×10^{15} GeV.

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