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NEON experiment: detectability for extragalactic sources and hardware status

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As a pioneering km^3-scale neutrino detector, the IceCube Observatory has established the feasibility of high-energy neutrino astrophysics by confirming the existence of astrophysical neutrinos, and has provided evidence for several potential extragalactic sources, such as TXS 0506+056, NGC 1068, and NGC 4151. To advance the field further, neutrino telescopes with a larger volume and higher precision are essential. To this end, we proposed the NEutrino Observatory in the Nanhai (NEON), a detector to be deployed in the South China Sea with a physical volume of about 10 km^3, which is currently under development. Given the anticipated high performance of NEON, we considered non-jetted active galactic nuclei (AGNs) as one of the most promising targets. By adopting specific models including the magnetically-powered corona model and the radiatively inefficient accretion flow (RIAF) model, we evaluated the detectability of such extragalactic sources with NEON and calculated the expected all-flavor neutrino event number after oscillation for 10 years of observation. The results demonstrate that NEON should be able to detect extragalactic sources at distances of up to 300 Mpc. Among these, a source with the X-ray luminosity and distance of NGC 1068 represents a prime candidate, especially in the several-to-hundred TeV energy range. Moreover, we have conducted preliminary tests on the key hardware components for the NEON experiment. The reliability of the photomultiplier tubes (PMTs), front-end and readout electronics, as well as mechanical structures has been verified by these trials.

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1. Introduction

Neutrino telescopes are essential for both physics and astrophysics studies. As one of the most well-known detectors, the IceCube Observatory first identified extraterrestrial neutrinos [1], demonstrating the feasibility of high-energy neutrino astrophysics. It has also provided evidence for several neutrino sources, such as TXS 0506+056 [2], NGC 1068 [3], and NGC 4151 [4]. Moreover, KM3NeT operates with a portion of its planned array and has detected the highest-energy neutrino event to date, called KM3-230213A [5]. However, due to limited statistics, none of the potential sources has reached the 5σ significance. Additionally, the substantial positional uncertainties resulting from the angular resolution of neutrino experiments can significantly complicate the association of some events with known astrophysical counterparts. To address these limitations, a few groups have proposed next-generation neutrino telescopes, such as IceCube Gen2 and P-One. Chinese researchers are also developing three neutrino detector proposals, namely NEON, HUNT, and TRIDENT. These high-performance facilities are expected to illuminate crucial scientific questions and yield groundbreaking discoveries in high-energy neutrino astrophysics.

Among them, NEutrino Observatory in the Nanhai (NEON) is proposed to be located in the South China Sea with a physical volume of approximately $10\,\mathrm{km}^3$. Its conceptual design and detailed methodology can be found in reference [6]. The simulation and analysis framework NEONSim has been developed for the project, consisting of particle interaction, simulation, and reconstruction. Following the data processing of this framework, we derived the expected atmospheric background, effective area, and sensitivity. Figure 1 (a) presents the residual atmospheric muon background, with deployment depths set at 1700 m and 3500 m. It is worth noting that the 3500 m depth exhibits a lower background compared to the 1700 m case, especially at energies above 1 PeV, demonstrating the effectiveness of deep-sea shielding in suppressing the atmospheric muon background. However, considering the superior self-veto capability [6], the deployment depth of 1700 m nevertheless remains a viable option. The neutrino effective area that depends on the physical area and the zenith angle is presented in Figure 1 (b). Since our reconstruction method for muon neutrinos is more refined, this analysis is restricted to this channel. Notably, our anticipated muon neutrino effective area at 100 TeV shows an enhancement of approximately one order of magnitude over IceCube [7]. Finally, by combining the atmospheric muon background analysis with the atmospheric neutrino background from the Honda model [8], we obtained the sensitivity curve for NEON, which will be provided in the following section.

2. Detectability of extragalactic sources with NEON

With a larger effective area and good angular resolution [6], NEON is expected to explore extragalactic sources within a certain number of years. Among these, non-jetted AGNs as steady sources are considered one of the most promising candidates. They are more abundant than jetted AGNs and continuously emit radiation and neutrinos. Their absence of strong jets and opaque environment facilitate the intrinsic absorption of high-energy γ rays, which is consistent with the GeV observation by *Fermi*-LAT [9]. Consequently, the long-term observation of neutrinos can provide a unique opportunity to study the hadronic processes.

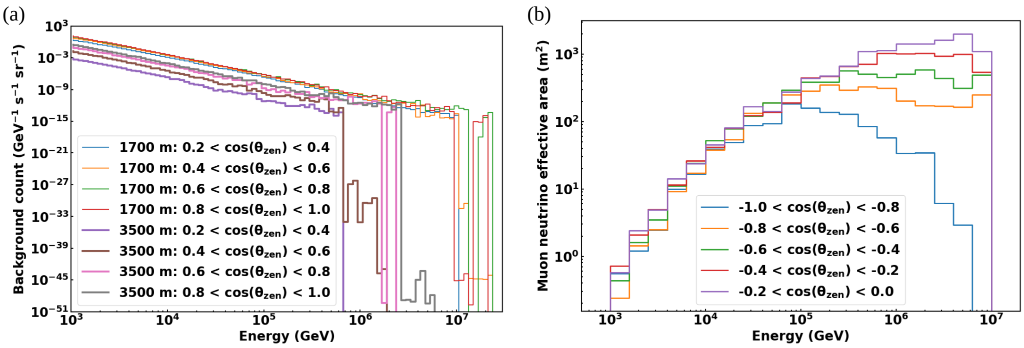

Figure 1: Performance evaluation of NEON. Panel (a) shows the atmospheric muon background after filtering for NEON, with different zenith angle. The deployment depths of 1700 m and 3500 m are considered. The steep decline at high energies is caused by the strong attenuation of atmospheric muons with increasing energy. Panel (b) gives the muon neutrino effective area for zenith angles exceeding 90°.

To assess the detectability of such sources with NEON, we adopt theoretical models that encompass non-jetted AGNs across a broad range of luminosities: the magnetically-powered corona model [10] for luminous AGNs (referred to as corona model hereafter) and the radiatively inefficient accretion flow (RIAF) model [11] for low-luminosity AGNs (LLAGNs). For both models, protons are accelerated through magnetic reconnections and/or plasma turbulence. These accelerated protons then interact with cold protons from the corona and accretion disk, as well as with photons emitted from these regions, leading to the production of high-energy neutrinos. These two models can be distinguished by their photon emission. The photon spectra of luminous AGNs exhibit prominent peaks in the ultraviolet to optical band, known as the big blue bump [12], which are generated by the accretion disk. In contrast, LLAGNs lack a standard optically thick disk, and therefore the big blue bump no longer exists. The absence of this feature significantly reduces the proton cooling rate in LLAGNs compared to luminous AGNs, thereby allowing protons to be accelerated to considerably higher energies.

The process of proton acceleration is described by the Fokker–Planck equation [10, 11]. We can obtain the accelerated proton spectrum by analytically solving this equation. The neutrino flux from an individual source is subsequently derived from the proton spectrum based on the proton-proton interaction model [13] and the photomeson production model [14]. In the calculation, we consider both the conventional and extreme cases for each AGN model. Figure 2 presents the expected neutrino spectral energy distribution (SED) compared to the sensitivity of NEON for all scenarios. For the corona model, we first adopt the X-ray luminosity and the distance of the well-known NGC 1068 [15], which verifies the capability of NEON to detect such sources. After that, we adopt a high X-ray luminosity of 1.0×10^{46} erg s^{-1} and estimate the maximum detection distance of NEON for luminous AGNs. The result is approximately 300 Mpc, which corresponds to a redshift of about 0.07 based on Hubble's law. For the RIAF model, the results indicate that the predicted neutrino SED from a source possessing the Hα luminosity and distance of NGC 4565 [16], the brightest observed LLAGN, is too weak for NEON to detect. Furthermore, even for an LLAGN with the highest Hα luminosity [16], detection would require a distance comparable to that of Centaurus A.

As discussed, NEON is capable of observing non-jetted ANGs at distances of up to 300 Mpc.

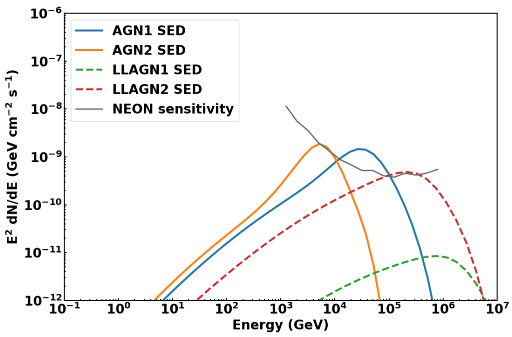

Figure 2: Detectability of extragalactic sources with NEON. The sensitivity curve is derived from 10 years of observation with a deployment depth of 3500 m. AGN1: X-ray luminosity 2.5×10^{43} erg s^{-1}, distance 10.1 Mpc (similar to NGC 1068 [15]). AGN2: X-ray luminosity 1.0×10^{46} erg s^{-1}, distance 300.0 Mpc. LLAGN1: Hα luminosity 3.5×10^{40} erg s^{-1}, distance 9.7 Mpc (similar to NGC 4565 [16]). LLAGN2: Hα luminosity 4.4×10^{41} erg s^{-1}, distance 4.0 Mpc.

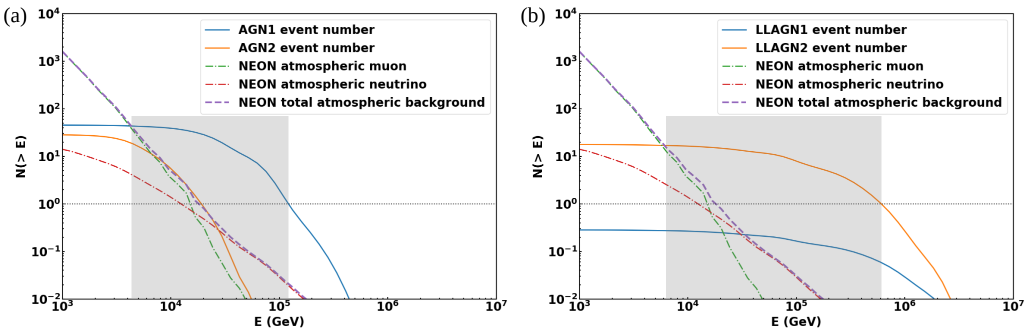

Figure 3: Expected all-flavor neutrino event number after oscillation for NEON over 10 years of observation. Panels (a)-(b) show the results for luminous AGNs and LLAGNs, respectively. The definitions of AGN1, AGN2, LLAGN1, and LLAGN2 are consistent with Figure 2. The explanation of the gray shaded regions is provided in the text.

To evaluate the detection potential, we calculate the anticipated all-flavor neutrino event number after oscillation of NEON using the following equation

$$N_\nu(> E_\nu) = \int d\Omega \int_{E_\nu}^{\infty} dE'_\nu \phi'_\nu A^\nu_{\text{eff}},\ \phi'_\nu = \frac{t_{\text{obs}} L_{E'_\nu}}{4\pi d^2 E'_\nu}, \tag{1}$$

where A^ν_{eff} is the muon neutrino effective area of NEON, ϕ'_ν denotes the neutrino fluence of an individual source, $L_{E'_\nu}$ represents the neutrino luminosity per energy of the source, and t_{obs} stands for the observation time. Notably, in the calculation, we assume that the effective areas for all flavors are equal to that of the muon neutrino. Figure 3 provides the results for 10 years of observation, along with the atmospheric background. The gray shaded region marks energies where events from a source exceed one and surpass the background. It is worth noting that an NGC 1068-like source is of particular significance to NEON from several TeV to approximately 100 TeV. This implies that NEON is poised to achieve the statistical significance necessary to reveal the origin of high-energy astrophysical neutrinos, thereby helping to resolve a key question in astrophysics.

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Table 1: Timing error test results for the front-end and readout electronics

Channel	σ_{arrival} (ns)	σ_{TOT} (ns)	Channel	σ_{arrival} (ns)	σ_{TOT} (ns)
shell a ch1	0.70	0.89	shell c ch1	0.36	0.80
shell a ch2	0.50	0.68	shell c ch2	0.36	0.53
shell a ch3	0.41	0.61	shell c ch3	0.36	0.56
shell a ch4	0.41	0.78	shell c ch4	0.41	0.70
shell b ch1	0.42	0.46	shell d ch1	0.48	0.59
shell b ch2	0.46	0.66	shell d ch2	0.49	0.61
shell b ch3	0.75	0.66	shell d ch3	0.49	0.82
shell b ch4	0.72	0.76	shell d ch4	0.72	0.71

[1] σ_{arrival}: standard deviation of the measured signal arrival time.
[2] σ_{TOT}: standard deviation of the measured signal TOT.

3. Current progress and future plans of NEON hardware

In addition to theoretical work, hardware development is equally crucial for the NEON experiment. PMTs serve as the primary sensors for detecting Cherenkov light produced by neutrino charged-current interactions, and their performance is vital to the success of the experiment. We compared the key characteristics of 3-inch PMTs manufactured by North Night Vision and Hamamatsu [17]. To improve efficiency, we are developing a batch-testing platform that uses an optical fiber splitter to test eight PMTs simultaneously.

The analog signals from the PMTs are processed by the front-end and readout electronics. We developed a system capable of handling data from 16 channels simultaneously, whose final output contains only the arrival time and time-over-threshold (TOT) for each signal. The test results for the system, using a standard input signal of 10 kHz with a pulse width of 10 ns, are shown in Table 1. All timing errors are below 1 ns, and the data packet loss rate during transmission is lower than 0.001‰. Our test utilized a 10 MHz master clock distributed to the slave unit, which guarantees synchronization.

Three iterative DOM versions are produced, each with enhanced electronics. All internal components are mounted on 3D-printed support brackets and housed within outer glass shells. After assembly, each DOM is evacuated to seal the glass enclosure. Finally, leak and pressure tests are conducted to ensure safe operation in the deep-sea environment.

To date, two preliminary underwater experiments have been conducted in the South China Sea and Qiandao Lake [6], successfully verifying the long-term stability of our hardware. The next trial will focus on achieving synchronization across multiple DOMs and detecting muon events, thereby validating the capability of the system for scientific research.

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