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Proposal for the High Energy Neutrino Telescope

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The Large High Altitude Air Shower Observatory (LHAASO) has observed tens of gamma-ray sources with significant emission above 100 TeV. These gamma-ray sources are probably the Galactic accelerators of PeV cosmic-rays. Thus, high energy neutrinos above 100 TeV are expected to be observed from these PeVatron candidates. We propose the Huge Underwater high-energy Neutrino Telescope (HUNT) with instrumented volume up to 30 km^3 to search for neutrino sources above 100 TeV, which will help us to identify the PeVatrons in our Galaxy and understand the acceleration of PeV cosmic-rays in the deep universe. Here, we present some preliminary results of the telescope simulation, the performance evaluation and the pathfinder experiment.

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1. Introduction

The origin of high energy cosmic-rays has been a mystery for decades. Under the confinement of Galactic magnetic field, the observed cosmic rays up to several PeV are believed to originate from Galactic sources, called PeVatrons. Cosmic rays interact with the interstellar medium or the radiation field, leading to the emission of neutrinos and gamma-rays. LHAASO has discovered that gamma-ray sources with significant emission above above 100 TeV are widely present in the Milky Way [1]. The observation of multi-hundred TeV neutrinos from these sources with a significance over 5σ will provide crucial evidence to identify PeVatrons.

In the past decade, high-energy neutrino astronomy has experienced rapid development. IceCube has observed the astrophysical neutrinos from the direction of TXS 0506+056 (3.5σ) [2], NGC 1068 (4.2σ) [3], and the Galactic plane (4.5σ) [4] since the operation from 2008. In addition to km^3-scale detectors (KM3NeT [5], Baikal-GVD [6], P-ONE [7]), the proposal for 8 km^3-scale detector has also been put forward (IceCube-Gen2 [8], TRIDENT [9]).

Here, we propose the HUNT project, a 30 km^3 neutrino telescope. The primary scientific goals of this project are centered around the effective and significant detection of high-energy neutrino sources within the Milky Way in order to identify PeVatrons in our Galaxy. Additionally, this project also aims at providing clear constraints on the types and properties of extragalactic neutrino sources, as well as gain insights into the mechanisms for the acceleration and propagation of high energy cosmic-rays.

2. Detector Design

Taking into account the experimental physics goals and the construction costs, the HUNT array is designed with 2304 strings, with an average spacing of around 130 m between each string (see Figure 1). Each string consists of 24 Optical Modules (OMs), with a spacing of 36 m, and a total depth of 860 m. With this layout, the geometric volume of the detector reaches 30 km^3. There are currently two telescope sites under consideration, Lake Baikal and South China Sea.

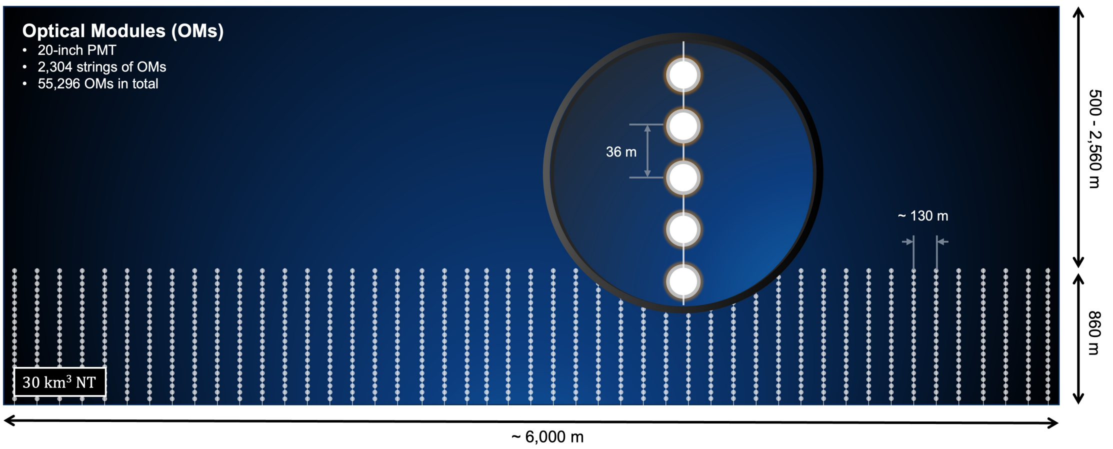

Figure 1: The schematic diagram of the HUNT array.

As shown in Figure 2, the optical sensitive device used in the OMs is a 20-inch PMT (Photomultiplier Tube). Each OM is integrated with LED calibration light sources, high-voltage and low-voltage module power supplies, readout electronics systems, temperature and humidity sensors, pressure gauges, and other equipments.

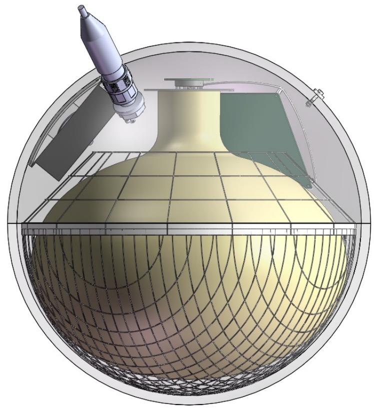

Figure 2: Optical module design schematic. A 20-inch PMT encapsulated inside a 23-inch glass sphere.

The clock distribution system adopts White Rabbit technology and protocol developed by CERN, whose accuracy is less than 1 ns. The electronics have a waveform sampling and storage capability of 500 MHz to 1 GHz. An acoustics positioning system will be installed in the array to monitor the position of all the strings in real-time with an accuracy of 20 cm. Both LED light sources and lasers will be used to calibrate the relative timing differences between all the sensors, with an accuracy better than 0.3 ns.

The trigger system is planned to adopt a global online trigger mode. This means that the charge and timing information of the OMs will be first transmitted to the on-shore data acquisition system for event selection, and then the digital waveform information within the relevant OMs will be read out. All data transmission will be done through optical fibers, with on-shore infrastructure including power distribution stations, data acquisition systems, and computational storage centers.

3. Simulation

We simulated the $30\,\mathrm{km}^3$ cylinder array and calculated the effective area for track events. The charged current cross section σ_{CC} for deeply inelastic neutrino-nucleon scattering calculated by [10] and the analytical approximation of inelasticity distribution $\mathrm{d}p/\mathrm{d}y$ for charged current interactions [11, 12] are adopted in our lepton generator. The muon energy loss after traveling a column density $\mathrm{d}X$ is approximated by the equation $\mathrm{d}E/\mathrm{d}X = -\alpha - \beta E$. We take the energy loss parameters (see Table 1) in different media calculated by PROPOSAL [13].

We sampled N_{inj} neutrinos uniformly on the disk perpendicular to the incident direction of neutrinos and N of them have trajectories that could pass through the array. The probability of a neutrino generating a muon and entering the array is

$$p_{\mathrm{obs}} = \int e^{-\sigma_{\mathrm{CC}} N_{\mathrm{A}} X_\nu} \sigma_{\mathrm{CC}} \mathrm{d}X_\nu \int_{E_{\mu,\mathrm{min}}/E_\nu}^{1} \frac{\mathrm{d}p}{\mathrm{d}y} \mathrm{d}y, \tag{1}$$

Medium	α, [10^{-3} GeV cm^2 g^{-1}]	β, [10^{-6} cm^2 g^{-1}]
Air	2.81	3.58
Water	2.49	4.22
Rock	2.21	5.31

Table 1: The parameters for muon energy loss in different media.

where $E_{\mu,\mathrm{mim}} = (\alpha/\beta + E_0)e^{\beta X_\mu} - \alpha/\beta$ is the minimum energy required for the muon to reach the array before cooling down to $E_0 = 10$ GeV. The reconstructed energy uncertainty is assumed to be $\Delta\log E_{\mathrm{rec}} = 0.3$ [5]. The effective area can be expressed as

$$A_{\mathrm{eff}}(E_\nu, \theta_z) = p_{\mathrm{select}} \frac{A_{\mathrm{disk}}}{N_{\mathrm{inj}}} \sum_i^N p_{\mathrm{obs,\,i}}, \tag{2}$$

where p_{select} represents the efficiency in event selection. It is assumed that the motion directions of muons are the same as the incident directions of their parent neutrinos.

Two sites are considered: the Lake Baikal (51.8° N) and the South China Sea (17.4° N). The arrays are deployed at depths ranging from 500 m to 1360 m in Lake Baikal and from 2560 m to 3420 m in the South China Sea. The modified PREM models are used for the Earth Model [14].

In the study of detection efficiency of muon tracks, we use Geant4 to simulate the propagation of muons from 10 TeV to 100 TeV inside the array. As the OM simulation has not been completed, we replace each OM with a glass sphere and set half of sphere as photon-detection area according to the orientation and quantum efficiency of PMT. The attenuation length in the water measured by Baikal-GVD is adopted in the simulation. The noises in the environment (e.g., ^{40}K radioactivity) and the electrical noises of PMT are not considered.

We adopt the following event selection criteria: 1) The minimum number of photons reaching the surface of the OM is 3, and there are at least 7 OMs that satisfy this condition; 2) The combined number of photons detected by the OMs that satisfy the first condition is no less than 60. We find that the detection efficiency for up-going events ($\theta_z > 80°$) is above 85% at the energies above 30 TeV, and drops to $\sim$ 70% at 10 TeV.

In the analysis of angular resolution, we reconstruct muon track with weighted time residual method:

$$\chi^2_{\mathrm{WTR}} = \sum_i^N w_i \left(\frac{t_i(X,\theta) - T_i}{\sigma_i} \right)^2, \tag{3}$$

where σ_i is the time detection error of the i-th OM, $w_i = q_i/\sum q_j$ is the fraction of charge number in the i-th OM, and $t_i - T_i$ is the time residual between the theoretical expectation and the detection. The median value of opening angle between the reconstructed direction and the true muon direction is better than 0.05 degree when the track length exceeds 6000 m.

4. Prospects for Detecting Galactic Sources

In the neutrino source search using through-going track events, we only count up-going events with zenith angle $\theta_z > 80°$. The signal to noise ratio is much worse for $\theta_z < 80°$. In the long-term search for point-like sources, the signal event number is given by

$$n_s = \int dt \int dE_\nu \phi^{\mathrm{astro}}_{\nu_\mu+\bar{\nu}_\mu} A'_{\mathrm{eff}}(E_\nu, \delta_s), \tag{4}$$

where

$$A'_{\mathrm{eff}}(E_\nu, \delta_s) = \frac{1}{1\ \mathrm{day}} \int A_{\mathrm{eff}}(E_\nu, \theta_z) g(\theta_z(\delta_s, t))\mathrm{d}t. \tag{5}$$

is the time-weighted average effective area over a day, and $g = 1$ when $\theta_z \geq 80°$ ($g = 0$ when $\theta_z < 80°$). Figure 3 shows the average effective area for 100 TeV and 1 PeV neutrinos. The event selection resulted in a 40% reduction in event number at 100 TeV and a 30% reduction at 1 PeV. Lake Baikal site shows larger effective area in the direction of Galactic center, while South China Sea site covers a larger range of declination.

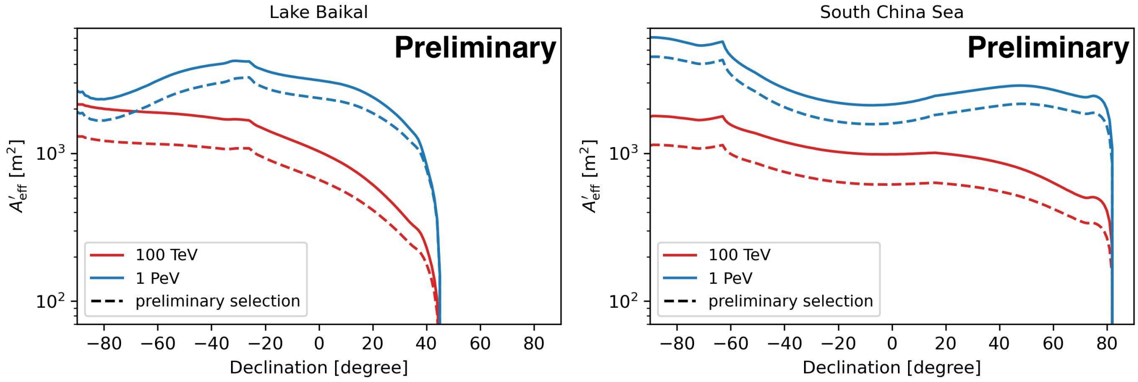

Figure 3: Time-weighted average effective area. The dashed lines show the result after event selection.

The number of background events is given by

$$n_b = \int \mathrm{d}t \int \mathrm{d}\Omega \int \mathrm{d}E_\nu (I^{\mathrm{atm}}_{\nu_\mu+\bar{\nu}_\mu} + I^{\mathrm{astro}}_{\nu_\mu+\bar{\nu}_\mu}) A_{\mathrm{eff}}(E_\nu, \theta_z) g(\theta_z(\delta_s, t)), \tag{6}$$

where $I^{\mathrm{atm}}_{\nu_\mu+\bar{\nu}_\mu}$ is the atmospheric muon neutrino flux and $I^{\mathrm{astro}}_{\nu_\mu+\bar{\nu}_\mu}$ is the diffuse astrophysical muon neutrino flux [15] in the unit of GeV^{-1} cm^{-2} s^{-1} sr^{-1}. The software MCEq [16] is utilized to model the atmospheric neutrino flux.

As both sites are more sensitive to the Southern Sky, we choose a PeVatron candidate HESS J1702-420A [17] to assess the detection capability of HUNT. The intrinsic extension of HESS J1702-420 is around $\sigma_s = 0.06°$. If all the gamma-rays observed are generated by π^0 decay in p-p interactions, we expect to observe the neutrino flux following the black line in Figure 4.

We estimate the statistical significance of observation with the binned likelihood as

$$L = \prod_{i,j} \frac{n_s S_{ij} + n_b B_{ij}}{n_{ij}!} e^{-n_s S_{ij} - n_b B_{ij}}, \tag{7}$$

where n_s (n_b) is the total number of signal events (background events) observed, S_{ij} (B_{ij}) is the probability of signal events (background events) in the i-th spatial bin and the j-th energy bin, and

n_{ij} is the number of events observed in the same bin. We approximate the median significance (Z_A) by replacing the data by the corresponding expectation values [18]:

$$Z_A = \sqrt{2\left((n_s + n_b)\ln\left(1 + \frac{n_s}{n_b}\right) - n_s\right)}. \tag{8}$$

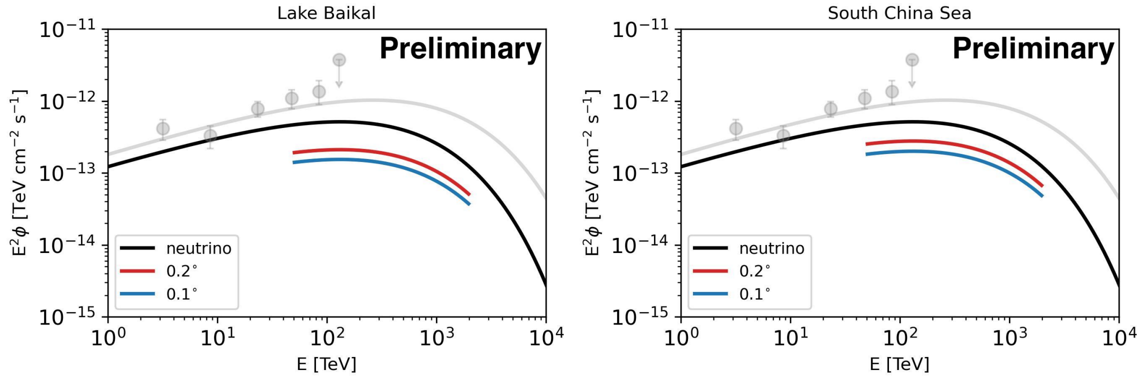

Figure 4: The ten-year discovery potential for neutrinos from HESS J1702-420A for different angular resolutions. The gray dots show the gamma-ray measurements by H.E.S.S. [17]. The gray line represents the fitted gamma-ray spectrum, and the black line represents the neutrino flux expected if all the gamma-rays are produced through π^0 decay.

The spatial distribution of signals is assumed to follow the 2D Gaussian with the extension $\sigma = \sqrt{\sigma_s^2 + \sigma_{\text{det}}^2}$. We referenced the angular resolution of in-water neutrino telescopes at the similar energies and assumed $\sigma_{\text{det}} = 0.2°$ [5, 9]. We anticipate detecting the neutrinos in the energy range from 50 TeV to 2 PeV at the significance level of 5σ with 10 years of operation at Lake Baikal (South China Sea), if 41% (54%) of the multi-hundred gamma-rays are from π^0 decay (see Figure 4). The energy distributions of event rate are shown in Figure 5.

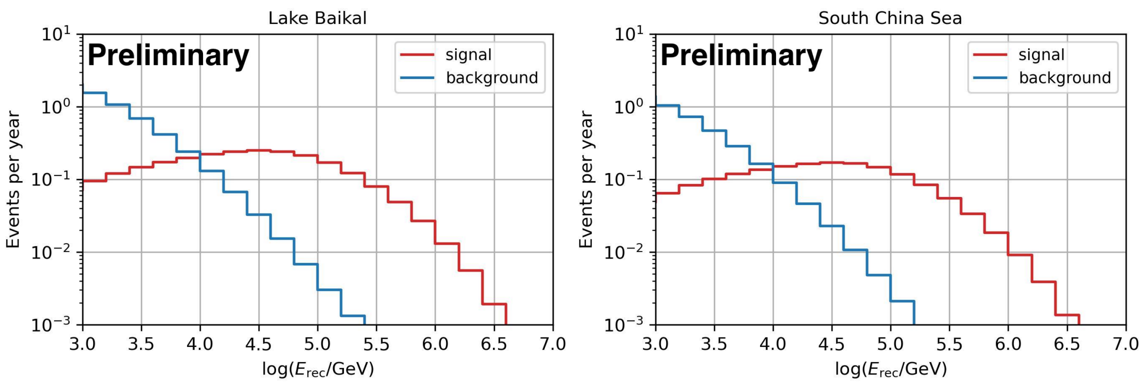

Figure 5: The event rate per bin for background events (blue) and signal events (red). The event numbers are counted within the solid angle $\Omega = \pi(1.6\sigma)^2$. The signal neutrinos follow the black line in Figure 4 from 50 TeV to 2 PeV.

5. Pathfinder Experiment

We conducted the pathfinder experiment in the waters of the Xisha Islands in the South China Sea in February 2023. The experiment apparatus is composed of five parts, the LED calibration system, two OMs (8-inch PMTs), two gamma-ray spectrometers, a 23-inch glass sphere and a ballast, which are fixed on a string from top to bottom. The string was deployed to a depth of 1100 m for 5.5 hours and 1800 m for 12.8 hours.

The long-distance LED calibration system works well in the experiment. The time calibration accuracy can reach 0.4 ns for bright LED pulses. Two gamma-ray spectrometers, a scintillation crmcystal gamma spectrometer and a Cadmium-Zinc-Telluride (CZT) gamma-ray spectrometer, in the fourth glass sphere measured the gamma-ray background directly. The radioactivity for ^{40}K and ^{212}Pb are shown in Table 2. The 23-inch glass sphere remained mostly intact after the 18-hour pressure resistance test. We also searched for coincidence hits within 200 ns window, but no significant signals were found.

Scintillation Crystal Gamma Spectrometer			
Depth [m]	Radionuclide	Channel 0 [Bq/L]	Channel 6 [Bq/L]
1800	^{40}K(1460 keV)	15.1 ± 1.3	17.1 ± 0.1
1100		14.8 ± 2.8	19.4 ± 2.3
CZT Gamma-ray Spectrometer			
Depth [m]	Radionuclide	Channel 0 [Bq/L]	Channel 2 [Bq/L]
1800	^{212}Pb(238.6 keV)	1.2 ± 0.2	0.9 ± 0.2
1100		0.97 ± 0.4	1.02 ± 0.3

Table 2: The radioactivity for ^{40}K and ^{212}Pb measured by gamma-ray spectrometers.

6. Outlook

In the following research, we will optimize the detector simulation and reconstruction algorithms, considering more details such as lepton energy loss, the response of PMTs, and the impact of noises. We are also integrating the program CRMC [19] into Geant4 to realize the physical process above 100 TeV. By taking these factors into account, our objective is to enhance the overall performance and accuracy of the reconstruction process. In the upcoming phase of the experiment, we will deploy a prototype string into the optical array of Baikal-GVD.

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