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High Energy Astrophysical Neutrino Flux and Galactic Center Dark Matter Annihilation Search with Hyper-Kamiokande

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Tau neutrinos are among the least studied particles in the Standard Model due to the challenges in producing and detecting them. One of the primary sources of tau neutrinos is astrophysical events, where they are mainly produced through flavor oscillations. Evidence for atmospheric ν_τ appearance has already been reported by Super-Kamiokande, providing the first confirmation of this phenomenon. At higher energies, the astrophysical ν_τ flux has been detected by neutrino telescopes like IceCube, although identifying the tau component of the flux, especially at TeV-scale energies, remains difficult due to the short lifetime of the tau lepton and its similarity to electron neutrinos or neutral current interactions. In this work, we explore the potential of water Cherenkov experiments like Super-Kamiokande and its next-generation upgrade, Hyper-Kamiokande, to measure the astrophysical neutrino flux and isolate the tau component. Such measurements would be essential not only as the first low-energy detection of the astrophysical neutrino flux but also as a critical tool to probe Beyond the Standard Model (BSM) scenarios involving tau neutrinos, such as those linked to dark matter interactions.

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1. Introduction

High-energy astrophysical neutrinos are valuable messengers from the most energetic environments of the Universe. Due to their weak interactions and ability to travel long distances without absorption or deflection, they carry direct information about their production sites. These properties make neutrinos one of the main sources of information in the recently established field of multi-messenger astronomy, together with gravitational waves and cosmic rays (CRs), among others.

Hyper-Kamiokande (HK), the next generation water Cherenkov detector currently under construction in Japan, will have excellent sensitivity to ν oscillation parameters, as well as to neutrinos originating from various sources [1–4]. Here we present its potential to study astrophysical neutrinos up to the TeV energy scale, together with its capability to perform indirect dark matter (DM) searches [1, 2].

Notably, Super-Kamiokande has already observed atmospheric ν_τ appearance [5], demonstrating that water Cherenkov detectors can identify tau neutrinos.

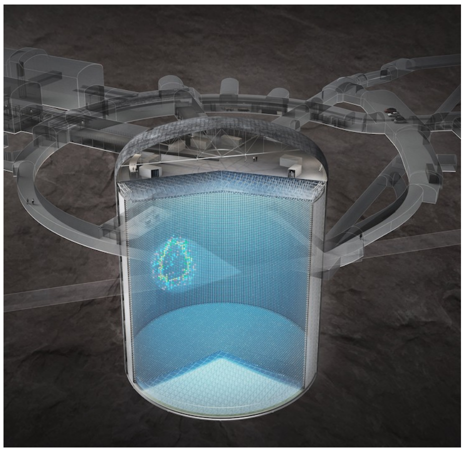


Figure 1: Schematic view of HK FD [6].

Atmospheric neutrinos are produced by interactions of primary CRs with nuclei in the atmosphere, leading to charged hadrons whose decays generate this flux of neutrinos. Although their study has been and remains very promising, they also represent a significant background for some neutrino analyses. This is the case of our study, where both the astrophysical neutrino flux and DM searches are limited by the atmospheric neutrino background.

2. Hyper-Kamiokande

HK builds on the legacy of its predecessors, Kamiokande and Super-Kamiokande (SK). The design and construction of the detector are currently in progress, with data taking planned to begin in 2028. It will be sensitive to neutrinos from different sources, highlighting astrophysical ν and indirect DM searches, thanks to its wide energy coverage from a few MeV to ~10 TeV.

The experiment is composed of two near detectors (upgraded ND280 and INGRID), one intermediate (IWCD) and the far detector (FD), which is overburdened by 600 m of rock under Mount Nijyugo-yama, Tochibora site, ~295 km away from the neutrino accelerator source J-PARC in Tokai, Japan. The FD consists of a cylindrical tank with 68m in diameter and 71 m in height, filled with ~260 kton of ultra-pure water, resulting in ~190 kton of fiducial mass, separated into two regions. On the one hand, the inner detector (ID), where 20,000 improved 50 cm diameter photomultipliers (PMTs) will be installed, together with 800 multi-PMTs (mPMTs) modules, each housing 19 smaller PMTs to improve directional reconstruction and enhance sensitivity. On the other hand, the outer detector (OD), which acts as a shield against low-energy background and as an active veto for cosmic ray muons [1].

3. Astrophysical neutrino flux

Cosmic rays can be accelerated in astrophysical shock fronts up to relativistic velocities, leading to a power-law energy spectrum of the form $E^{-\gamma}$, where γ denotes the spectral index. There are two main ways of detecting these relativistic charged particles: either directly, as CRs, or indirectly, as synchrotron radio emission. In addition, in the same astrophysical environments where CRs and radiation are produced, the interaction of CRs with surrounding matter and photon fields can lead to the production of neutrinos. In this analysis, the flux per flavor is modeled using a power-law spectrum [7] as

$$\phi(E) = \text{norm} \times 2.40 \times 10^{-12} \times \left(\frac{E}{300\ \text{GeV}}\right)^{-\gamma}. \tag{1}$$

The observation of high-energy neutrinos provides insight into astrophysical neutrino production, which is closely related to the poorly understood production and acceleration mechanisms of CRs. The spectral index γ, together with the normalization factor, carries information about the neutrino sources and their environments.

For the neutrino produced by pion decay, we expect the astrophysical neutrino flux to have a ν_e:ν_μ:ν_τ ratio of 1:1:1 due to neutrino oscillations over astronomical distances. In Fig. 2, we show this result together with other neutrino flux components in the (10-10^4) GeV energy range, such as the conventional [8] and prompt [9] atmospheric neutrino fluxes, as well as the flux of neutrinos originating from the Galactic Plane [10]. We also include the dark matter-induced neutrino flux from the Galactic Center considering a DM mass of 6 TeV, the latter computed using the PPPC4DMID framework [11], the same framework we used to compute the ν spectra from DM annihilation in Section 5.2.

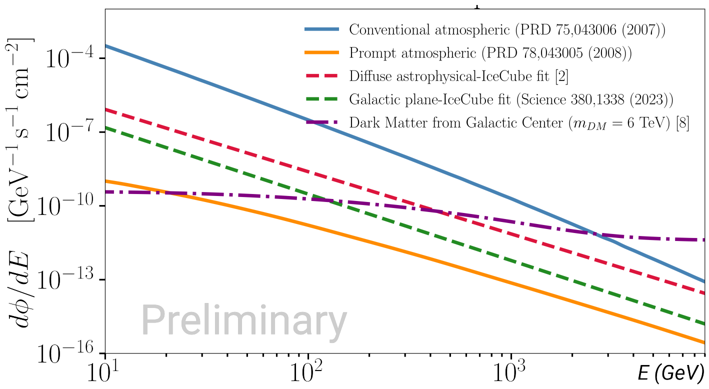


Figure 2: Neutrino flux components are shown: conventional and prompt atmospheric fluxes, diffuse astrophysical flux, galactic plane flux, and dark matter flux from the Galactic Center.

4. Neutrinos from dark matter

Neutrinos can also be generated when DM particles χ annihilate or decay in regions of high density, such as the Galactic Center (GC) of the Milky Way. In this analysis we assume Majorana DM particles and focus on neutrinos produced by DM annihilation in the GC.

The expected flux at Earth is given by

$$\frac{\mathrm{d}^2\Phi_\nu}{\mathrm{d}E_\nu\,\mathrm{d}\Omega} = \frac{\langle\sigma v\rangle}{2}\,\frac{1}{4\pi m_\chi^2}\sum_f B_f\,\frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu}\,J(\psi), \tag{2}$$

where $J(\psi)$ is the astrophysical J-factor, which quantifies the DM distribution along the line of sight. For annihilation,

$$J(\psi) = \int_{\mathrm{l.o.s.}} \rho^2\left[r(l,\psi)\right]\mathrm{d}l, \tag{3}$$

where $\rho(r)$ is the DM density profile and l denotes the line of sight (l.o.s.). Assuming the Navarro-Frenk-White (NFW) profile [12]

$$\rho(r) = \frac{\rho_s}{(r/r_s)\,[1+r/r_s]^2}\,, \tag{4}$$

for the Galactic DM distribution with $r_s = 20$ kpc and $\rho_s \simeq 0.33$ GeV cm^{-3}, the average J-factor in a cone of 10^{-5} sr around the GC is $\bar{J}(10^{-5}\mathrm{sr}) \sim 2\times10^{23}$ GeV^2 cm^{-5}, which normalizes the expected ν flux in HK.

5. Sensitivity analysis

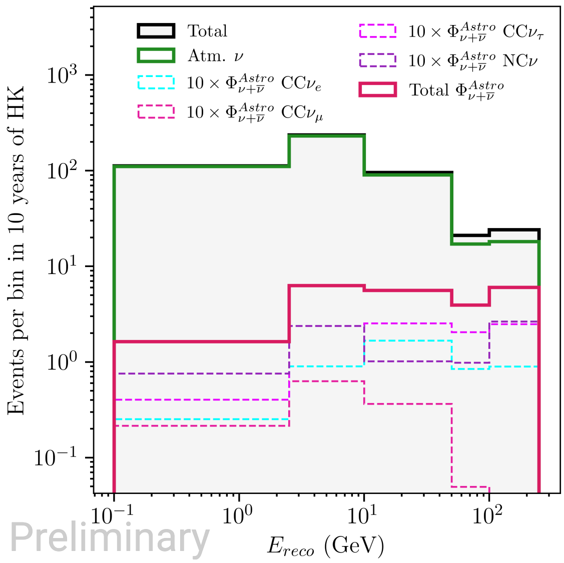


Figure 3: Expected number of events in 10 years of HK Multi-Ring τ-like down-going sample. Note the $\times10$ scaling for visualization purposes.

To estimate the sensitivity of HK, either for the astrophysical ν flux or for indirect DM searches, we assume its performance will be similar to that of the current SK experiment. For this purpose, we use the Monte Carlo algorithm developed in [13], enhanced using SK reports [14, 15]. This framework includes information about the neural network used to separate the tau component, together with recent efficient identification techniques based on sample patterns observed in water Cherenkov detectors.

5.1 Astrophysical neutrino flux

From O(TeV) to $O(10^2$ TeV), the measurement at HK is limited to the ν_μ component through Partially Contained (PC) and Up-going muon samples (UpMu) (μ-like samples). For lower energies, below $O(100GeV)$, ice- and water-based detector technologies have already demonstrated the ability to identify ν_τ even in the presence of background [16, 17], which is mainly observed in the so-called Fully-Contained samples (FC) [15].

We developed our analysis at the GeV scale, considering two main points: τ-like event tagging uses digitized output from SK's neural net classifier [14], and zenith angle binning is reduced

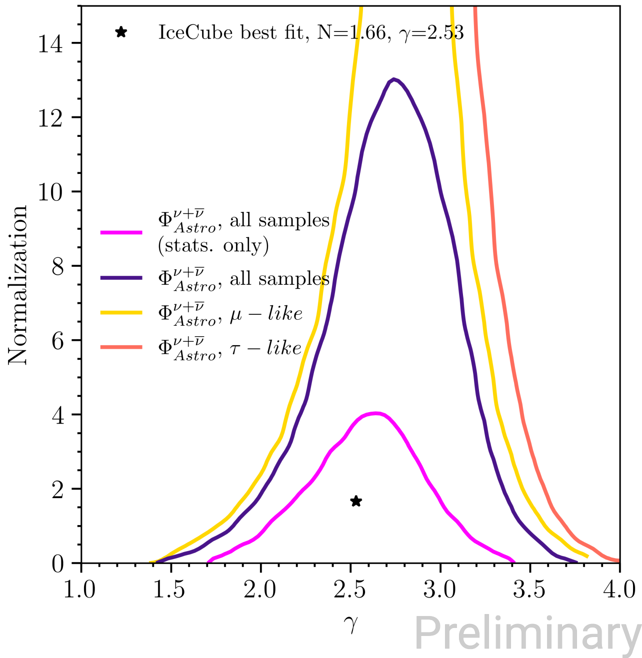


Figure 4: Expected 1σ sensitivity contours for the astrophysical neutrino flux parameters, assuming 10 years of HK exposure.[7].

to up-going (dominated by atmospheric ν oscillations) and down-going (mostly astrophysical ν_τ, assuming isotropy) for separation.

We expect to identify the ν_τ component within a certain energy range, taking advantage of the fact that the dominant background to astrophysical neutrinos is the isotropic atmospheric flux. In the (10-10^4) GeV range, Fig. 3 shows that at high energies the sum of the astrophysical charged-current (CC) and neutral-current (NC) components (solid black line) becomes comparable to the atmospheric neutrino flux. At lower energies, although the total astrophysical flux remains subdominant, the atmospheric background contains very few ν_τ due to their suppressed production in cosmic ray interactions and the limited oscillation probability at these energies [18]. This relative enhancement of the astrophysical ν_τ component suggests that Hyper-Kamiokande could achieve sensitivity to it across the full energy range considered [1, 2, 13, 15].

In Fig. 4 we use the τ-like FC sample together with the μ-like PC and UpMu samples from the astrophysical flux. The contours under the 1σ sensitivity lines represent the parameter space that each sample can constrain for the astrophysical neutrino flux parameters (γ and normalization), which provide information about neutrino sources and their environments (see Eq.1). The τ-like sample shows some sensitivity, although the ν_μ sample is better matched to the best-fit value reported by IceCube [7], which we take as the true parameters (★): norm = 1.66, γ = 2.53.

This analysis probes the promising HK sensitivity to the astrophysical neutrino flux in the (10-10^4) GeV range. The τ-like sample is most useful for lower energies in the range studied, while the μ-like sample dominates in the (~300-$O(10^4)$) GeV range. However, IceCube reports better results at high energies. Thus, the astrophysical neutrino flux analysis with HK could provide a

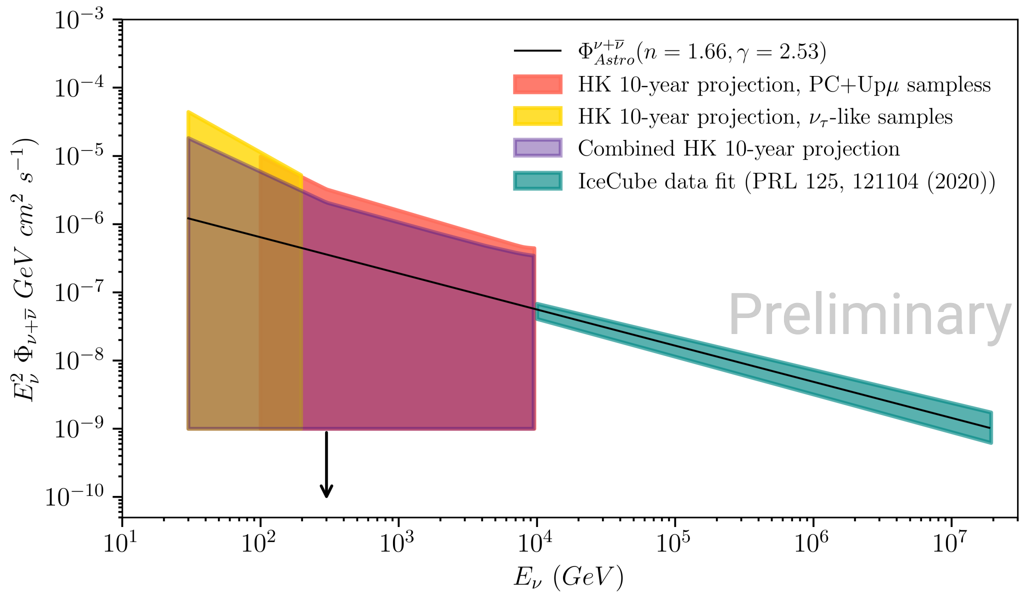
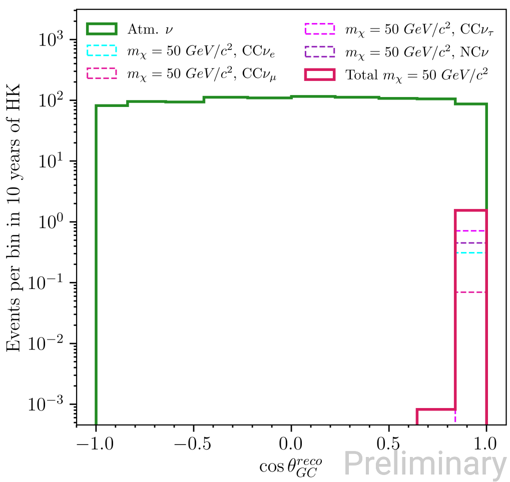


Figure 5: Comparison of 1σ allowed regions for the astrophysical ν flux parameters between HK and IceCube, where IceCube data fit used is from [7].

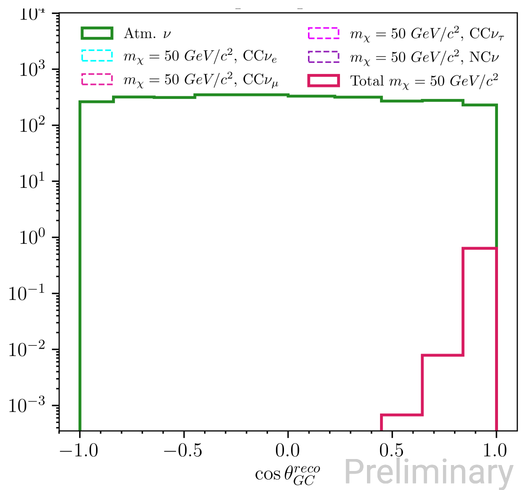
complementary measurement to IceCube's sensitivity at energies below a few TeV, as shown in Fig. 5.

5.2 Dark matter

High-energy neutrino sources such as DM annihilation in the GC can also be explored with HK. For the following figures Fig. 6a and Fig. 6b, we consider $m_\chi = 50$ GeV, corresponding to the DM (χ) mass, and $\langle\sigma v\rangle = 10^{-25}$ cm^3 s^{-1}, the velocity-averaged annihilation cross section, as expected from the thermal relic scenario [19].



(a) Multi-Ring τ-like sample.



(b) μ-like PC sample.

Figure 6: Expected number of events in HK over 10 years.

In the case of GC DM annihilation indirect search analysis, we followed a strategy similar to that used for the astrophysical neutrino flux. However, instead of using energy as the primary parameter to compare with the atmospheric neutrino background, we analyze directionality, focusing on neutrinos from the GC, where DM particles annihilate, taking advantage of HK's improved directional reconstruction capabilities. Given that the atmospheric neutrino flux is isotropic, any excess from the direction of the Milky Way's GC could indicate a non-atmospheric origin. Assuming HK points directly towards the GC (i.e., $\cos\theta_{\mathrm{GC}}^{\mathrm{reco}} = 1$), we have analyzed two samples separately: a Multi-Ring τ-like sample (Fig. 6a) and a μ-like partially contained (PC) sample (Fig. 6b).

Assuming the null hypothesis of DM ($\langle\sigma v\rangle = 0$), we evaluated HK's sensitivity to the $\chi\chi \to \nu\bar{\nu}$ channel. Our analysis indicates that HK could potentially probe DM annihilation with optimal sensitivity in the mass range (10–10^4) GeV/c^2. For comparison, sensitivity projections for IceCube, SK, and ANTARES can be found in [20], and for KM3NeT in [21].

6. Conclusions

In this work, we have explored the potential of HK to study astrophysical neutrinos and search for high-energy neutrino signals from DM annihilation in the GC. Our analysis demonstrates that HK has promising sensitivity to astrophysical neutrinos at low and intermediate energies, in the (10–10^4) GeV range. The identification of ν_μ events benefits from PC and UpMu samples, providing excellent sensitivity at higher energies, while ν_τ detection and identification allows probing an upper bound of the astrophysical neutrino flux at lower energies ($\mathcal{O}(10)$–300 GeV). These measurements would provide a complementary view of the astrophysical neutrino flux relative to IceCube, particularly below a few TeV, and offer additional constraints on the spectral index and normalization of the flux, which are directly linked to the underlying neutrino sources and their astrophysical environments.

Furthermore, HK's improved directional reconstruction capabilities enable the study of neutrinos from high-density regions such as the GC, allowing searches for signals of DM annihilation. By analyzing Multi-Ring τ-like and μ-like PC samples, we estimate that HK could achieve optimal sensitivity to the $\chi\chi \to \nu\bar{\nu}$ channel in the mass range of 10–10^4 GeV/c^2 under the null DM hypothesis. This sensitivity complements existing projections from IceCube, SK, ANTARES, and KM3NeT, expanding the discovery potential for indirect DM detection.

Overall, HK promises to play a crucial role in improving our understanding of astrophysical neutrinos and their sources. Its unique capabilities to isolate the ν_τ component at low energies, combined with complementary ν_μ measurements, make it a powerful tool. Moreover, its directional sensitivity to potential DM-induced signals further enhances its role in multi-messenger astrophysics. Future measurements with HK will not only refine our knowledge of the astrophysical neutrino flux, but also provide essential constraints on BSM physics scenarios involving tau neutrinos, such as those linked to DM interactions or other exotic phenomena. These efforts will significantly enhance our understanding of high-energy neutrino astronomy and particle physics.

References

[1] K. Abe *et al.*, Hyper-Kamiokande Design Report (2018).

[2] K. Abe *et al.*, Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential — (2011), arXiv:1109.3262.

[3] T. Yano, Solar neutrino physics at Hyper-Kamiokande, PoS ICRC19 (2019), Inspire-HEP:1819225.

[4] K. Abe *et al.*, Supernova Model Discrimination with Hyper-Kamiokande, The Astrophysical Journal (2021), doi:10.3847/1538-4357/abf7c4.

[5] K. Abe *et al.* (Super-Kamiokande Collaboration), Evidence for the appearance of atmospheric tau neutrinos, Phys. Rev. Lett. 110, 181802 (2013), arXiv:1206.0328.

[6] Hyper-Kamiokande Collaboration, Hyper-Kamiokande official website, https://www-sk.icrr.u-tokyo.ac.jp/en/hk/ (accessed 16 September 2025).

[7] M. G. Aartsen *et al.*, Phys. Rev. Lett. 125, 121104 (2020).

[8] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D 75, 043006 (2007), arXiv:astro-ph/0611418.

[9] R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008), arXiv:0806.0418 [hep-ph].

[10] IceCube Collaboration, Science 380, 1338 (2023), doi:10.1126/science.adc9818.

[11] M. Cirelli *et al.*, JCAP 03, 051 (2011).

[12] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. 462, 563 (1996).

[13] C. A. Argüelles *et al.*, Phys. Rev. X 13, 041055 (2023).

[14] Z. Li *et al.*, Phys. Rev. D 98, 052006 (2018).

[15] T. Wester *et al.* (Super-K), Phys. Rev. D 109, 072014 (2024).

[16] M. G. Aartsen *et al.*, Phys. Rev. D 99, 032007 (2019).

[17] A. Albert *et al.*, JHEP 03, 142 (2025).

[18] N. F. Bell *et al.*, JCAP 09, 019 (2020).

[19] G. Steigman, B. Dasgupta, and J. F. Beacom, Phys. Rev. D 86, 023506 (2012).

[20] K. Abe *et al.* (Super-K), Phys. Rev. D 102, 072002 (2020).

[21] S. Aiello *et al.*, arXiv:2411.10092 [astro-ph.HE] (2024).