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# Prospects for neutrino astrophysics with Hyper-Kamiokande

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Hyper-Kamiokande is a multi-purpose next generation neutrino experiment. The detector is a two-layered cylindrical shape ultra-pure water tank, with its height of 64 m and diameter of 71 m. The inner detector will be surrounded by tens of thousands of twenty-inch photosensors and multi-PMT modules to detect water Cherenkov radiation due to the charged particles and provide our fiducial volume of 188 kt. This detection technique is established by Kamiokande and Super-Kamiokande. As the successor of these experiments, Hyper-K will be located deep underground, 600 m below Mt. Tochibora at Kamioka in Japan to reduce cosmic-ray backgrounds. Besides our physics program with accelerator neutrino, atmospheric neutrino and proton decay, neutrino astrophysics is an important research topic for Hyper-K. With its fruitful physics research programs, Hyper-K will play a critical role in the next neutrino physics frontier. It will also provide important information via astrophysical neutrino measurements, i.e., solar neutrino, supernova burst neutrinos and supernova relic neutrino. Here, we will discuss the physics potential of Hyper-K neutrino astrophysics.

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PoS(ICRC2021)1193

## 1. Introduction

Hyper-Kamiokande (Hyper-K, HK) is a next generation water Cherenkov detector planned in Japan [1–3], as a successor of the Super-Kamiokande (Super-K, SK) experiment [4]. With the dimensions of the 71 m (D) × 60 m (H), a cylindrical water tank will provide the fiducial (total) volume of 0.188 (0.258) million metric tons (figure 1). They are 8 (5) times larger than those of Super-K. The target date for starting the operation is 2027. The inner detector will be surrounded by 20-inch diameter photodetectors and multi-PMT modules. The photo-coverage of 40 % is aimed to achieve, which corresponds to 40,000 of 20-inch PMTs. Here, we also discuss about an option to install 20,000 of 20-inch PMTs and thousands of multi-PMT modules. Thousands of 3-inch diameter photodetectors with wavelength shifting plates will be provided for the outer veto detector, to remove cosmic-ray muon backgrounds. The 20-inch photodetector, Box&Line dynode photo-multiplier tube Hamamatsu R12860, is newly developed for HK, to achieve twice larger detection efficiency for Cherenkov photons, the superior photon counting and timing resolution compared to that of SK (Hamamatsu R3600) [5]. It also has the high pressure tolerance for the usage below 60 m depth of water. The multiple-photosensor unit is also in our R&D for the detector [5, 6]. The detector will be located underground at Kamioka mine in Gifu Prefecture, with an overburden of ~600 meters or more of rock, which is equivalent to 1,620 meters or more of water. Charged particles, such as the products of neutrino interactions, are detected with the emitted Cherenkov photons. The number of photons and their arrival times on the photodetectors are used to reconstruct the energy and vertex of the particle, respectively. Hyper-K has various physics topics: search for CP violation in neutrinos, precise study of neutrino oscillations including determination of mass hierarchy and $\theta_{23}$ octant with beam and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

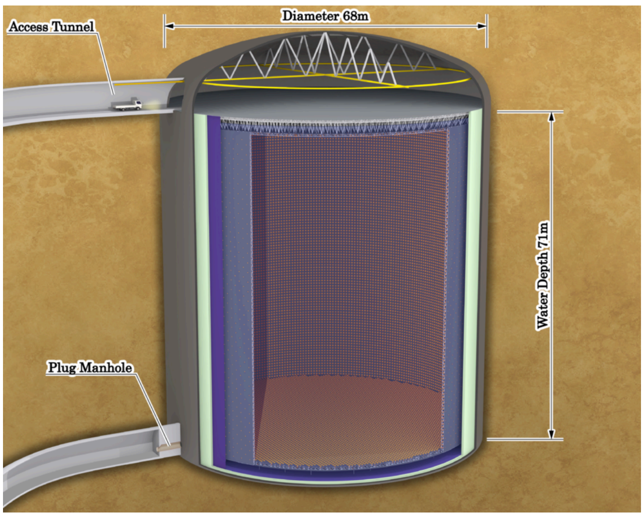


**Figure 1:** Schematic view of one Hyper-Kamiokande water Cherenkov detector [1]. Our collaboration aims at starting the observations at 2027. The tank will provide the fiducial volume of 0.188 Mt ultra pure water, with the dimensions of the 71 m (D) × 60 m (H).

## 2. Solar Neutrino

The Sun is burning and emitting neutrinos with the nuclear fusion reactions, which are called as the pp-chain and the CNO cycle. They can be summarized as follows: $4p \to \alpha + 2e^{+} + 2\nu_e$. These processes are described with the standard solar model (SSM) [7, 8], which provides good predictions of the flux and energy spectrum of solar neutrinos. Our main observation target is the $^{8}$B neutrino, with its energy above our analysis threshold of $E_{vis} > 4.5$ MeV. Here, $E_{vis}$ is the visible energy of the neutrino event in water Cherenkov detector. It is smaller than the total energy of neutrinos by ∼1.5 MeV. They are observed through neutrino-electron elastic scattering, $\nu + e \to \nu + e$. The energy, direction, and time of the original neutrinos are measured through their recoil electrons. About 130 $\nu$-e scattering events will be observed in a day, while 15 $\nu$ events/day are observed at SK-I.

### 2.1 Solar Neutrino Oscillation

The solar neutrino measurement are capable of determining the neutrino oscillation parameters between neutrino mass eigenstates. Super-K [9], SNO [10] and several experiments [11–13] have been performed the neutrino oscillation measurement on the solar neutrinos. Figure 2 shows the latest results [14] of the allowed neutrino oscillation parameters, the mixing angle $\theta_{12}$ and the mass squared difference $\Delta m^2_{21}$ from all solar neutrino experiments, as well as the reactor neutrino experiment KamLAND [15]. The $\Delta m^2_{21}$ of $6.11^{+1.21}_{-0.68} \times 10^{-5}$ eV$^2$ is reported there by Super-Kamiokande collaboration, as the results of solar oscillation analysis combining Super-K and SNO measurements. The tension between solar and reactor best fit $\Delta m^2_{21}$ became rather small as ∼1.4 $\sigma$,

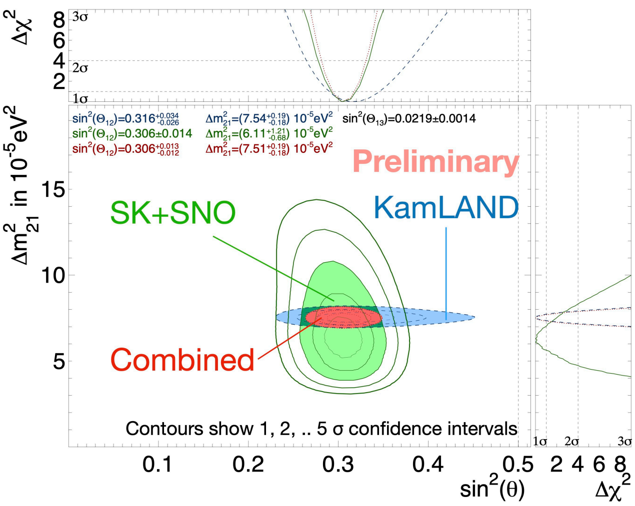


**Figure 2:** Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 $\sigma$ lines and 3 $\sigma$ area are shown[14]. The dashed green line is the combined results of SK and SNO.

comparing to ∼2 $\sigma$ tension with solar best fit $\Delta m^2_{21} = 4.8^{+1.5}_{-0.8} \times 10^{-5}$ eV$^2$ in 2016 [9].

The tension is mainly derived from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which was indicated by Super-K [16]. The asymmetry would arises from the terrestrial matter effect, i.e. the regeneration of the electron neutrinos through MSW matter effect in the Earth. The effect can be seen as a few percent more event rate in the nighttime, than that in the daytime. With Hyper-K, the day-night asymmetry effect can be measured precisely with our large detector volume. Assuming the solar best fit $\Delta m^2_{21}$ parameter at 2020, our measurement will be possible to prove the day-night asymmetry effect above 5 $\sigma$ (figure 3) with 10 years observation.

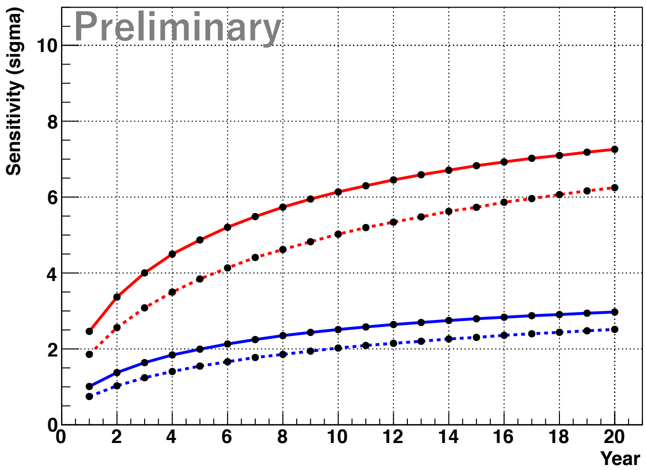


**Figure 3:** Day-night asymmetry observation sensitivity as a function of observation time. The red line shows the sensitivity from the no asymmetry, while the blue line shows from the asymmetry expected by the reactor neutrino oscillation. The solid line is for Hyper-K inner detector photo-coverage of 40%, while the dotted line is for 20% case. The systematic uncertainty of 0.3% is assumed here.

The solar neutrino survival probability upturn is also the interesting physics properties. It is predicted by MSW-LMA solution and possibly affected by physics beyond the standard model, such as non-standard interaction[17], mass-varying neutrino oscillation[18] and sterile neutrino[19], for example. The non-zero upturn sensitivity will be about $3\sigma$ ($4\sigma$) after the 10 years solar neutrino measurement with 4.5 MeV (3.5 MeV) threshold, even with the solar best fit oscillation parameters in 2020.

## 3. Supernova Neutrinos

Core collapse supernova explosions are the last process in the evolution of massive stars (>8 $M_\odot$). The energy released by a supernova is estimated to be $\sim 3 \times 10^{53}$ ergs and 99% of the energy is carried out by all three types of neutrinos and anti-neutrinos. The detection of supernova neutrinos gives direct information of energy flow during the explosions. From SN1987a, the Kamiokande, IMB, and Baksan experiments observed 25 neutrino events. It proved the basic scenario of the supernova explosion was correct. However, close to three decades later the detailed mechanism of explosions is still not known. The observation of new supernova with the large neutrino detector is desired. The multi-messenger observation with visible light, gamma-ray, x-ray, gravitational wave and Hyper-K will also reveal the supernova explosion in details.

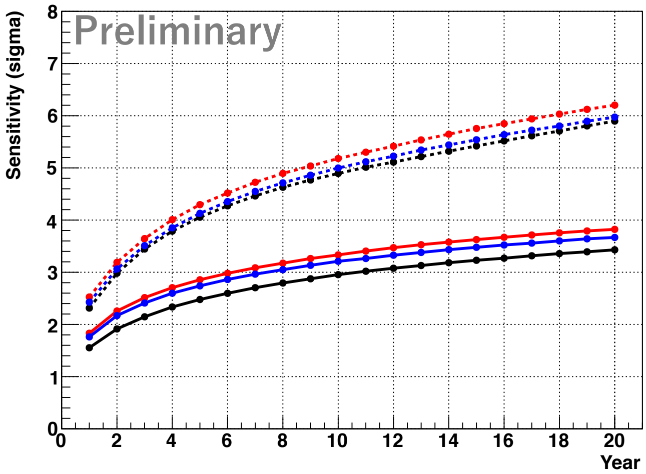


**Figure 4:** Discovery sensitivity for solar neutrino spectrum upturn as a function of the observation time. The solid line shows the case with the energy threshold of 4.5 MeV, while the dotted line shows the case with the energy threshold of 3.5 MeV. Black line shows the case with photo-coverage of 40%, solar best fit $\Delta m^2_{21}$ and $\theta_{12}$ in 2016. The red (blue) line shows the updated sensitivity for photo-coverage of 40% (20%) and solar best fit parameters in 2020.

The first and direct observation of supernova neutrinos is about the supernova burst neutrinos, which are released in several seconds after its onset of a burst. About 90% of signals at Hyper-K is inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). For each full volume of two inner detectors, we expect to see about 49,000-68,000 inverse beta decay events, 2,100-2,500 $\nu$-e scattering events, 80-4,100 $\nu_e$+$^{16}$O CC events, and 650-3,900 $\bar{\nu}_e$+$^{16}$O CC events, in total 52,000-79,000 events for a supernova explosion at halfway across our galaxy (10 kpc, figure 5). The statistical error will be small enough to compare several SN models, and so Hyper-K should give crucial data for further model predictions (figure 6). A new characteristic modulation of the supernova neutrino flux also can be tested with HK, which the recent computer simulations predict. In past simulation, the deceleration of the shock wave and resulting failed explosion were annoying problems. Recent simulations suggest that the shock wave will be heated efficiently by neutrinos to revival, due to the physical motions in a supernova, Standing Accretion Shock Instability (SASI) or convection, rotation of supernova are the examples. These models also predict the characteristic frequency modulation of neutrino flux, due to the motions in supernovae. The detection of these modulation will prove the neutrino as the driver of supernova explosions. Other topics for astrophysics and particle physics also can be examined, e.g. direct observation of black hole formations and mass hierarchy of neutrinos.

Another observation target is about the supernova relic neutrinos (SRN), produced by all past supernova explosions since the beginning of the universe and diffused. They must fill the universe and their flux is estimated to be a few tens/cm$^2$/sec. SRN contains the information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and the fraction of strange supernova explosions like dim supernovae or black hole formations (figure 7). Although searches for SRN have been conducted at large underground detectors, no evidence of SRN signals has yet been obtained, because of the small flux of SRN. With incoming detector update, Gd-loaded

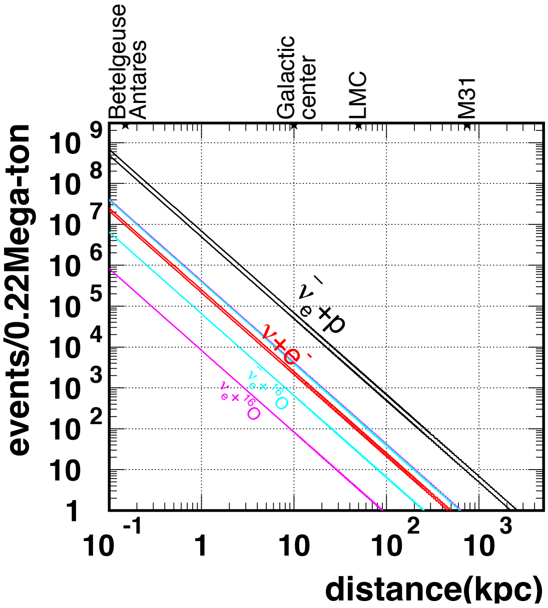


**Figure 5:** Expected number of supernova burst events for each interaction as a function of the distance to a supernova[3]. The band of each line shows the possible variation due to the assumption of neutrino oscillations.

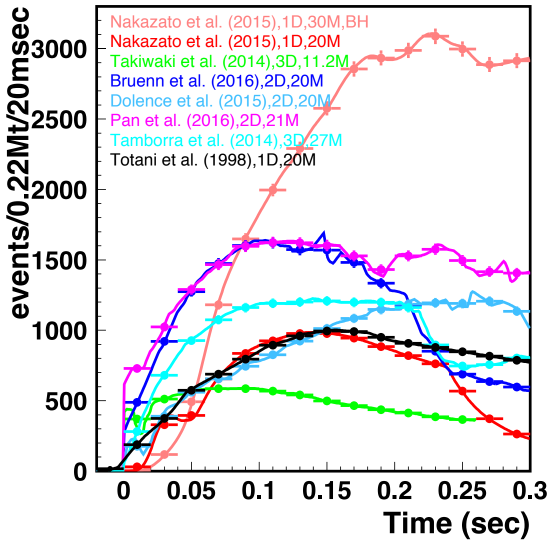


**Figure 6:** Inverse beta decay event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst[3]. The error bars show the statistical error.

Super-Kamiokande (SK-Gd) can be the discoverer of SRN. The number of event in SK-Gd detector will be 0.8-5 events/year above 10 MeV. Even though, it is still very interesting physics theme to measure and determine the precise flux of SRN. ~70 (40) SRN events are expected at 16-30 MeV by 10 years observation with the detector photo-coverage of 40% (20%). The significance will be 4.2 $\sigma$ and enough for confirming the discovery (figure 8). The significance will be 3 $\sigma$, in case of photo-coverage of 20%.

## 4. Summary

Hyper-Kamiokande is a next generation large water Cherenkov detector. Several studies are being performed, e.g. photosensor R&D, design and physics optimization. Solar neutrino measurement is one of the features of Hyper-K. Several precise measurements of solar neutrinos would be possible with Hyper-K and its high statistics, e.g. the solar neutrino oscillation, the search for physics beyond the standard model, the first measurement of hep process neutrino and also the seasonal variation measurement of the $^8$B neutrino flux. As a conclusion, Hyper-K will play a crucial role in the next neutrino physics frontier for both of particle physics and neutrino astrophysics.

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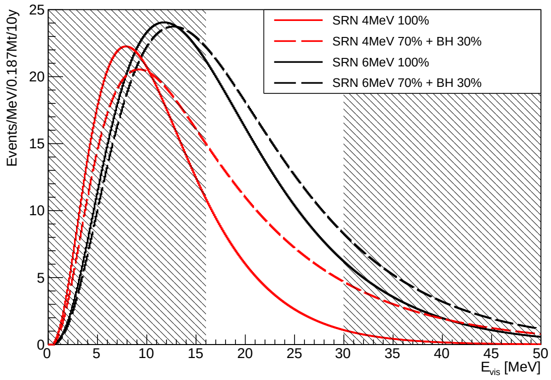


**Figure 7:** The expected SRN signal in 10 years observation is shown. Black line shows the case of supernova neutrino temperature of 6 MeV, and red shows the case of 4 MeV [20, 21]. Solid (dashed) line corresponds to the case, in which all the core-collapse supernovae emit neutrinos with the particular energy (30% of them form black hole and emit higher energy neutrinos with the temperature of 8 MeV). Shaded energy region shows the range out of SRN search window at Hyper-K.

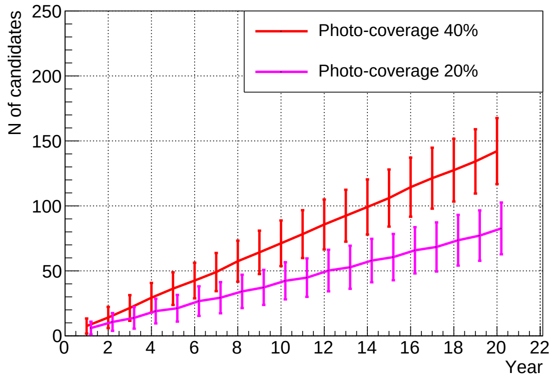


**Figure 8:** The figure shows the expected number of observed SRN events and its ambiguity as a function of observation period.

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PoS(ICRC2021)1193

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