PROCEEDINGS OF SCIENCE

Astrophysical neutrino search in KamLAND

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Neutrinos have been regarded as a unique tool for revealing the interiors of astronomical objects. KamLAND, which is a 1-kiloton liquid scintillator located in the Kamioka mine, detects electron antineutrinos through inverse beta decay. Due to its significant sensitivity in the energy region around a few MeV, KamLAND can detect supernova neutrinos (SNνs). To search for SNνs, we have performed a cluster event search and set an upper limit on the Galactic supernova rate. Neutrinos emitted a few hours before a supernova (pre-SNν) are also detectable. We have developed the combined alert system for pre-SNνs with the Super-Kamiokande group. In addition, we are developing a new background reduction scheme using a neural network to reduce atmospheric neutrino backgrounds in the supernova relic neutrino search. Other than SNνs, KamLAND has a sensitivity to neutrinos from primordial black holes, which are one of the candidates of dark matter. In this paper, we show the search progress of neutrinos from supernovae and primordial black holes.

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1. Introduction

The observation of supernova neutrinos (SNνs) from SN1987A [1–3] marked the dawn of neutrino astronomy. Due to the high transparency of neutrinos, we can gain insights into the interiors of stars through the observation of SNνs. Neutrinos are also available for the dark mater exploration. Primordial black holes (PBHs) are considered as one of the dark matter candidates and potential sources of astrophysical neutrinos [4]. The average energies of SNνs and neutrinos from PBHs are typically on the order of a few MeV to tens of MeV. Such neutrinos can be detected by Water-Cherenkov detectors and liquid scintillator detectors around the world.

2. KamLAND detector and detection channel

Kamioka Liquid-Scintillator Anti-Neutrino Detector (KamLAND) is located 1000 m underground beneath Mt. Ikenoyama. KamLAND consists of a 1-kiloton inner liquid scintillator and a 3.2-kiloton outer water-Cherenkov detector. More details of the KamLAND detector are described in [5]. During the neutrinoless double-beta decay search phase (KamLAND-Zen), an inner balloon was installed at the center of the detector, and this volume was vetoed for the astrophysical neutrino search. In this paper we show the studies of electron antineutrino ($\bar{\nu}_e$) events via inverse-beta decay reaction ($\bar{\nu}_e + p \to e^+ + n$) (IBD) from astrophysical sources. This reaction produces time-spatial correlated events: a prompt event, caused by the positron and its annihilation gamma rays, and a delayed event, resulting from neutron capture gamma rays. These sequential events are tagged using the delayed coincidence (DC) method.

3. Astrophysical neutrino study

Pre-supernova neutrino alarm

Neutrinos emitted before the core collapse of a massive star are known as pre-supernova neutrinos (pre-SNνs). The observation of pre-SNνs enhances our understanding of the stellar evolution and provides an early warning of supernovae. Since pre-SNνs have a lower averaged energy than SNνs, the prompt energy range is set to 0.9−4.0 MeV in the visible energy of prompt events. We have developed the combined pre-SN alarm system with Super-Kamiokande [6]. This system has been running since 2023 using the number of observed events from both detectors.

Additionally, we have developed a new alarm algorithm that utilizes not only the number of events but also the time evolution of pre-SNνs modeled by Patton [7]. The likelihood function under the background+signal condition is expressed as $\mathcal{L}(\mathrm{BG} + \mathrm{SIG})$ while under the background only condition it is expressed as $\mathcal{L}(\mathrm{BG})$ [8]. These likelihood functions are constructed from the rate term only (conventional analysis) and from the product of the rate and time evolution term (new analysis). Given the time before core collapse t and the time of observed events $\{t_i\}$, the likelihood ratio is given as [8]

$$l(t, \{t_i\}) = \log \frac{\mathcal{L}(t, \{t_i\}|\mathrm{BG} + \mathrm{SIG})}{\mathcal{L}(t, \{t_i\}|\mathrm{BG})}. \tag{1}$$

To compare the sensitivity of the conventional analysis and new analysis, we generate events with $\{t_i\}$ using Monte Carlo simulations and calculate the significance from the likelihood ratio. Figure

1 shows the sensitivity comparison between the conventional rate analysis and new analysis incorporating the time evolution. The new analysis provides higher significance than the conventional analysis, indicating that it can issue earlier alarms.

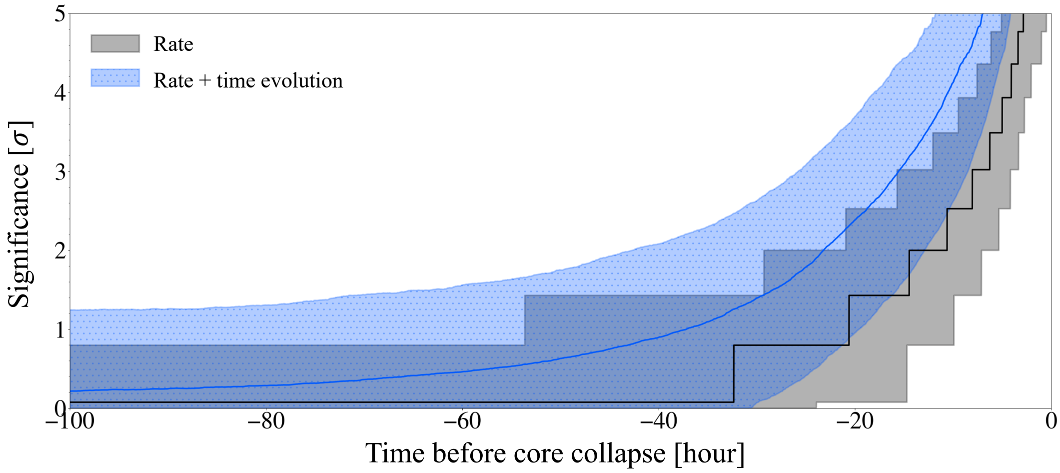

Figure 1: The significance toward the core collapse. The black line shows the significance of the rate only analysis and the blue line shows that of the rate and time evolution analysis. The gray band and light blue band represent 68% statistical fluctuations.

Supernova neutrino burst search

The average energy of SNν is about 10 MeV and the neutrino energy spectrum extends up to about 100 MeV. Therefore, we set the prompt energy range to 0.9−100 MeV and select DC candidates. To search for burst-like prompt events resulting from supernovae, the time difference between each DC candidate is required to be less than 10 s. As a result of the 5011.51-days cluster search, no clusters were found within the 10-s time window. The number of accidental cluster (a background for the SN burst search) is estimated from the expected DC events, with a value of 0.32. From these results, the 90% upper limit on the number of observed clusters is set to 2.1. We numerically calculate the SNν detectable range in KamLAND using Nakazato model [9]. This calculation indicates that KamLAND can observe more than 99% SNνs from the Galaxy. Based on the KamLAND's detectability, we set a 90% upper limit on the Galactic supernova rate as 0.15 yr^{-1}.

Supernova relic neutrino search

Supernova Relic Neutrinos (SRNs), which represent the integrated signal from past supernova neutrinos, provide important insights not only into the mechanisms of supernovae but also into the history of cosmic star formation. The flux of SRN dominates in the energy gap between the reactor and atmospheric neutrinos: in the neutrino energy range of 8−30 MeV. Also, a new SRN model suggests an enhancement in the SRN flux around 10 MeV [10]. For the SRN search in KamLAND, we define the prompt energy range as 8.5−30 MeV. The most dominant background source is the neutral current interaction of atmospheric neutrinos, as this interaction is also observed as a DC event.

To distinguish between the IBD signal and atmospheric neutrino background, we use a deep neural network developed by the KamLAND group, called KamNet [11]. KamNet has several key features: a spherical neural network to preserve detector symmetry, convolutional long-short term memory to capture time correlation, and drop out to prevent over fitting. The input consists of hit photomultiplier tube positions, charges, and timings while the output is a KamNet score. Given the limited amount of the IBD and atmospheric neutrino candidates in real data, we have to train KamNet with well-tuned simulated events. The simulation was tuned based on the assumption that light particles share similar hit information with each other, and the same applies to heavy particles. Consequently, simulated $e^+ + \gamma$ are tuned to replicate real $^{12}\mathrm{B}\ \beta^-$ decay while atmospheric neutrinos are tuned to reproduce real fast neutrons. Their hit timing distributions are consistent within a few % statistical uncertainties. The training results are shown in Figure 2. This trained KamNet model is able to reject 62% background with 90% signal acceptance.

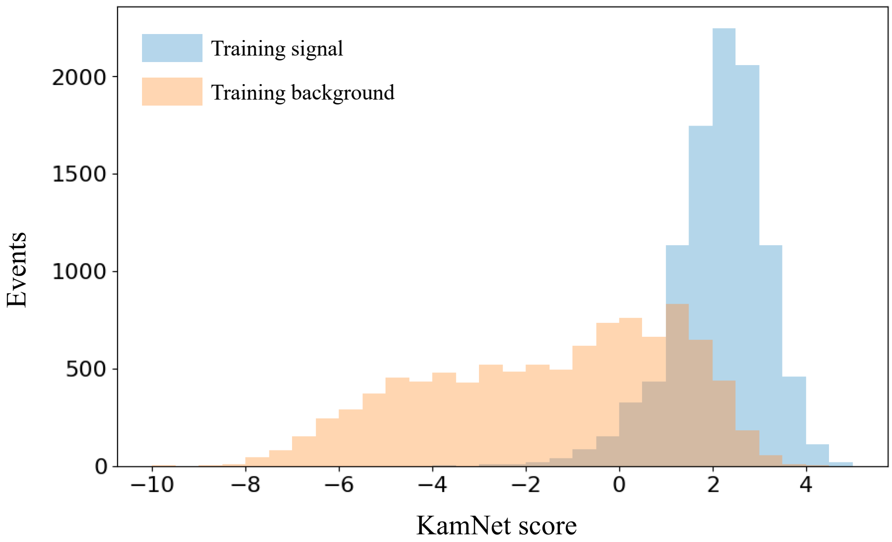

Figure 2: Training result of KamNet. The blue histogram represents the score distribution of simulated $e^+ + \gamma$ signals and the orange histogram represents the score distribution of simulated atmospheric neutrino backgrounds. The higher the score, the more signal-like the events are considered.

Search for neutrinos from primordial black holes

PBHs, one of the dark matter candidates, are thought to form from the gravitational collapse of the dense energy region in the early universe. They lose the mass through Hawking radiation emitting neutrinos either directly (the primary component) or from the decay of leptons and pions (the secondary component). The neutrino luminosities of each components are calculated by BlackHawk [12, 13]. Neutrinos emitted from PBHs with a mass range of 10^{15}–10^{17} g have an average energy of about 10 MeV and can be observed in KamLAND. To estimate the PBH neutrino flux on Earth, the PBH distribution is assumed to follow the dark matter distribution within the Galaxy [14] and to be uniform outside the Galaxy. Given the published KamLAND analysis result [15], we set upper limits on the PBH fraction, $f_{\rm PBH}$, defined as the ratio of the PBH energy density to the dark matter energy density in Figure 3. Our constrains are stricter than those provided by Super-Kamiokande [16] based on the open data [17] for PBHs with masses larger than 4×10^{15} g. Consequently, we reject the hypothesis that the dark matter consists solely of the PBHs with a mass range of more than 7×10^{15} g.

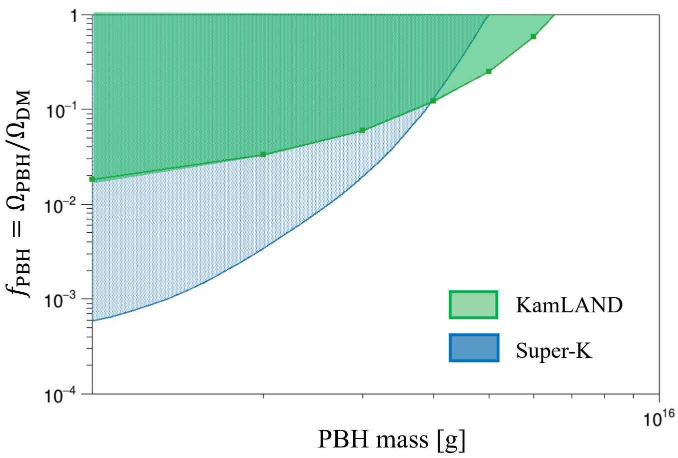

Figure 3: Constraints on the PBH fraction $f_{\rm PBH}$ in the PBH mass range of 10^{15}–10^{16} g. The green region shows constraints from KamLAND data [15] and the blue region shows constraints from Super-Kamiokande data [17].

4. Summary

We have conducted several studies on astrophysical neutrinos. The alarm sensitivity for the pre-SNνs has been improved by incorporating the time evolution of pre-SNν events. As a result of SNν burst search, no significant event clusters have been observed. As for SRN search, the development of a deep neural network to reduce atmospheric neutrino background is proceeding. We also search for neutrinos from PBHs. In the PBH mass region more than 7×10^{15} g, our result rejects the hypothesis that dark matter is explained only by primordial black holes.

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