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Pre-supernova neutrino alarm at KamLAND and its extension to an combined system with SK

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Pre-supernova neutrinos are released by thermal pair production and/or weak interaction at the end of stellar evolution. Detection of these neutrinos provides early warning of supernovae to astronomical detectors, including gravitational wave detectors and neutrino detectors. KamLAND is a 1-kiloton liquid scintillator neutrino detector located in Japan. KamLAND has the capability to detect pre-supernova neutrinos from nearby stars with low background conditions through inverse beta decay. Pre-supernova neutrino alarm system has been launched since 2015. This system is based on the significance of the statistical excess from background rate. Recently, we are preparing two major updates. The first one is to use information of time evolution. The other is a combined alarm system with Super-Kamiokade. The latter system has already been launched.

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[*] Speaker

1. Introduction

The stars with masses larger than 8–10$M_\odot$ evolve to synthesise heavy elements with nuclear burning and eventually become core-collapsed supernovae. Pre-supernova neutrinos are emitted by thermal pair production and/or weak interaction in the last stages of their stellar evolution. The detection of pre-supernova neutrinos helps us understand the stellar evolution. Furthermore pre-supernova neutrinos are also useful for early warning of supernovae.

Kamioka Liquid-scintillator Anti Neutrino Detector (KamLAND) is a 1-kiloton liquid scintillator (LS) detector located at 1000-m underground in the Kamioka mine in Japan. KamLAND consists of a water Cherenkov outer detector to shield cosmic muons and a LS inner detector to observe neutrinos. Since 2015, a 3.08 m-diameter inner balloon containing a xenon loaded LS has been installed at the center of the detector for neutrinoless double beta decay search [1]. The inner balloon region is not used for this analysis.

KamLAND detects anti-electron neutrinos ($\bar{\nu}_e$) from nearby pre-supernova stars via inverse beta decay (IBD) interactions. The energy threshold of this reaction is 1.8 MeV, which is lower than the average energy of pre-supernova neutrinos (~2 MeV). The IBD reaction emits a positron and a neutron ($\bar{\nu}_e + p \to e^+ + n$). The positron quickly deposits its kinetic energy into the LS and emits gamma-rays by annihilation with an electron (a prompt signal). The neutron is captured by a proton, (a carbon-12 nucleus) producing a 2.2 MeV (4.9 MeV) gamma-ray (a delayed signal). KamLAND suppresses background (BG) events by taking time and spacial correlation with the prompt and delayed signals.

KamLAND has launched a pre-supernova alarm system in 2015 [2]. This system is based on the significance of the statistical excess from the BG rate in the visible energy range of 0.9 – 4 MeV (rate analysis). The main BG is reactor $\bar{\nu}_e$ which is from Japanese nuclear power plants and geo $\bar{\nu}_e$ which is generated from radioactive isotopes in the Earth. The total BG rate is 0.17 events per day.

We present two approaches to improve the alarm system.

2. Rate+shape analysis

Rate+shape analysis is the alarm system considering the time spectrum in addition to rate analysis, and expects higher sensitivity than rate analysis. In recent years, a better understanding of the stellar evolution process has led to more accurate calculations of pre-supernova models. Rate+shape analysis depends on the pre-supernova models. We compare the sensitivity of rate and rate+shape analysis.

The likelihood functions of rate+shape analysis under both BG and BG+Signal conditions are shown as [3],

$$L(t, \{t_i\}|\mathrm{BG}) = \mathrm{Pois}(n(t), b_{\mathrm{exp}}) \prod_{i=1}^{n} \mathrm{Prob}(t_i|\mathrm{BG}), \tag{1}$$

$$L(t, \{t_i\}|\mathrm{BG{+}Signal}) = \mathrm{Pois}(n(t), s_{\mathrm{exp}} + b_{\mathrm{exp}}) \prod_{i=1}^{n} \mathrm{Prob}(t_i|\mathrm{BG{+}Signal}), \tag{2}$$

where s_{exp}, b_{exp} are the expected number of signal and BG events respectively, $\{t_i\}$ represents event time array over the past 200 hours (i=1,2,$\cdots n$), and n is equivalent to number of candidates.

The first factor is the rate factor. LThe likelihood function of the rate analysis is only composed of the rate factor. The second factor is the shape factor which is the proportional time spectrum.

To distinguish between BG and BG+Signal hypotheses, we define l_{SA} which is calculated by taking the likelihood ratio of eq. (1) and eq. (2) (see [3]) as

$$l_{\mathrm{SA}}(t, \{t_i\}) = \log \frac{L(t, \{t_i\}|\mathrm{BG+Signal})}{L(t, \{t_i\}|\mathrm{BG})}. \tag{3}$$

The distribution of l_{SA} is constructed by using n and $\{t_i\}$ generated by the toy MC method. We conduct a hypothesis test setting a threshold for l_{SA} based on the observations.

Figure 1 shows the comparison of the sensitivity of rate analysis and rate+shape analysis with a detection efficiency of 50%, which is the proportion of results exceeding the significance. Rate+shape analysis exhibits an earlier rise in significance than rate analysis. The alarm time of rate+shape analysis with 50% detection efficiency is 8 hours earlier than rate analysis when assuming Patton et al. [4] with normal mass ordering.

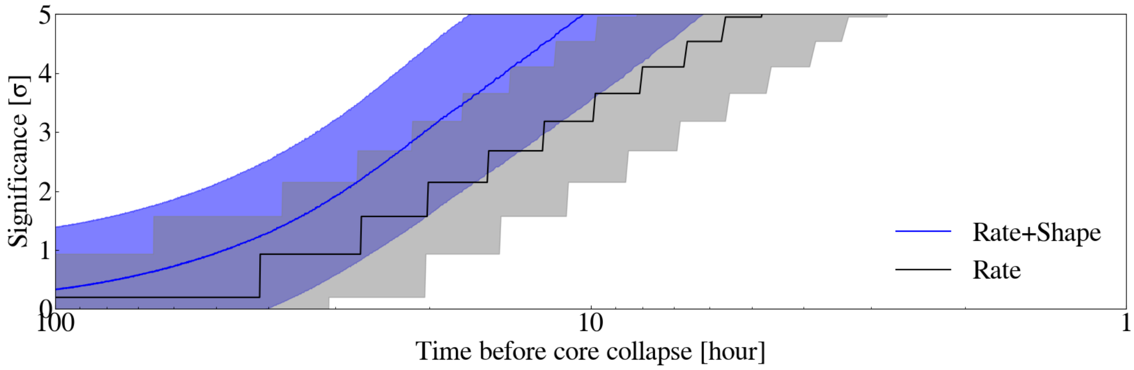


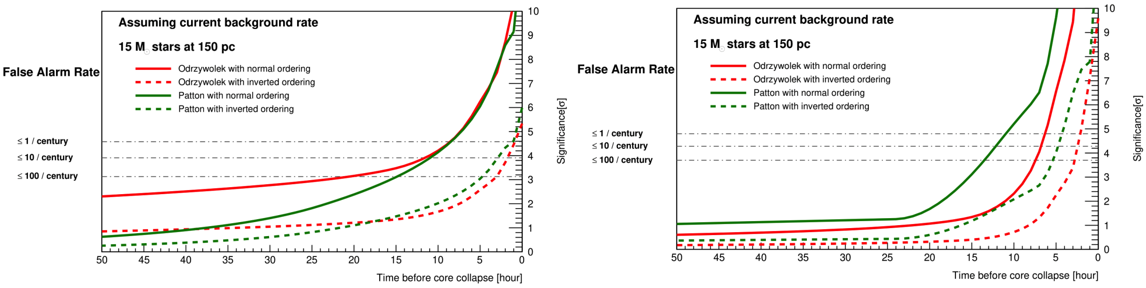
Figure 1: The significance of rate (grey) and rate+shape analysis (blue). The detection efficiency, i.e. the proportion of results exceeding the significance is 50%. The filled regions are 68% significance band. The signal comes from Betelgeuse-like star whose distance from the Earth is 150 parsecs and whose mass is $15M_{\odot}$. The assumed model is Patton et al. [4] with normal mass ordering.

3. Combined pre-supernova neutrino alarm with SK

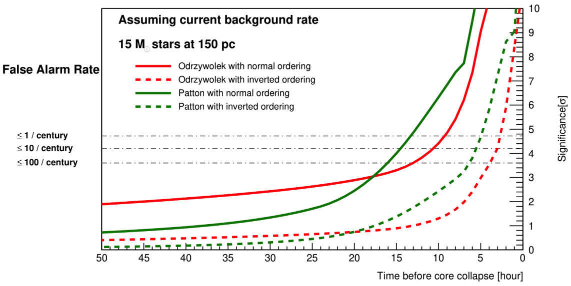
Independently of the section 2, the pre-supernova neutrino alarm system at KamLAND is combined with Super-Kamiokande (SK). SK is a 22.5-kiloton water Cherenkov neutrino detector located in the Kamioka mine in Japan [5]. The SK-Gd experiment, in which Gd is added to SK, is also sensitive to pre-supernova neutrinos. SK-Gd has launched a pre-supernova neutrino alarm system since 2021. The details of the SK pre-supernova alarm system are documented Mr. L. N. Machado's contribution in TAUP2023.

The likelihood function is the product of the Poisson likelihood functions for KamLAND and SK as, $L = \mathrm{Pois}\left(n^{\mathrm{KL}}, s_{\mathrm{exp}}^{\mathrm{KL}} + b_{\mathrm{exp}}^{\mathrm{KL}}\right) \times \mathrm{Pois}\left(n^{\mathrm{SK}}, s_{\mathrm{exp}}^{\mathrm{SK}} + b_{\mathrm{exp}}^{\mathrm{SK}}\right)$, where the subscripts SK and KL denote SK and KamLAND, respectively. Figure 2 is the result of these alarm sensitivities. The KamLAND alarm system which has lower BG events than SK is sensitive to early fewer pre-supernova neutrinos.

On the other hand, SK experiences a rapid increase in sensitivity due to its larger target mass than KamLAND. The combined alarm takes the advantages of both KamLAND and SK, and has better sensitivity than the individual alarms of these detectors.



(a) KamLAND **(b)** SK



(c) Combined

Figure 2: Time evolutions of expected KamLAND, SK and combined alarm sensitivities. The assuming models are Patton et al. [4] (red) and Odrzywolek et al. [6] (green) with normal and inverted mass ordering. The target star is a Betelgeuse-like star (15 $M_\odot$, 150 parsecs).

The combined alarm system has been running since 2023. This system issues an alarm when the false alarm rate reaches 1 per century and notifies registered external users. The combined alarm system is linked to the Gamma-ray Coordinates Network. You can access the combined alarm system at https://www.lowbg.org/presnalarm/.

4. Conclusion

This paper presents two approaches to improve the sensitivity of the pre-supernova neutrino alarm at KamLAND. First, we develop an earlier-issued alarm which use a time spectrum than the current alarm. Second, KamLAND is combined with SK. The combined alarm system is running.

References

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