PROCEEDINGS OF SCIENCE

Super-Kamiokande Pre-Supernova Alert System and combined system with KamLAND

L. N. Machado[a,*] **on behalf of the Super-Kamiokande Collaboration and the KamLAND Collaboration**

[a] *University of Glasgow, School of Physics and Astronomy, G12 8QQ, Glasgow, United Kingdom*

E-mail: lucas.nascimentomachado@glasgow.ac.uk

The Super-Kamiokande experiment is a neutrino observatory located in Japan. After the loading of gadolinium sulfate octahydrate to water in its detector, the Super-Kamiokande experiment has entered a new phase, known as SK-Gd. This new phase is characterized by the significant improvement in the experiment's sensitivity to low energy electron anti-neutrinos, thus providing more reliable data for the study of neutrino sources and interactions. SK-Gd has the potential of detecting yet-unobserved neutrinos from the Diffuse Supernova Neutrino Background and pre-supernova (preSN) stars, which are massive stars at the last evolutionary stage before core-collapse supernova (CCSN). The main cooling mechanism of preSN stars is the neutrino emission through different thermal and nuclear processes such as pair annihilation and beta decay, emitting high fluxes of electron anti-neutrinos. The detection of preSN neutrinos would not only help determine the neutrino mass hierarchy, but it could also provide early warnings for nearby CCSNs. In October 2021, Super-Kamiokande launched its preSN alarm. We report the sensitivity of the Super-Kamiokande detector to preSN neutrinos and information regarding the alert system. A joint alarm with the KamLAND experiment was developed to improve the sensitivity of preSN neutrinos and extending the early warning to CCSN.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

[*] Speaker

https://pos.sissa.it/

PoS(TAUP2023)210

1. The Super-Kamiokande Experiment

The Super-Kamiokande (SK) Neutrino Detector is a 50 kton water Cherenkov located in the Kamioka mine in Japan, overburden with 1000 m of rock. The SK detector is a stainless-steel cylindrical tank with approximately 39 m of diameter and 42 m height filled with water. The detector is divided in an inner detector with 11,000 20-inch photomultipliers tubes (PMTs), responsible for the overall event detection, and an outer detector with 1,885 8-inch PMTs facing the outside of the detector to veto cosmic ray muons. Figure 1 shows an illustration of the SK experiment.

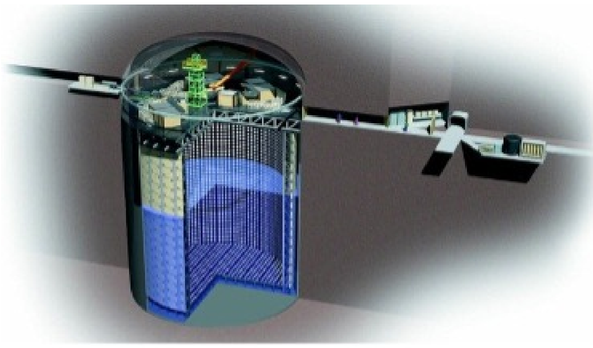


Figure 1: The Super-Kamiokande Experiment.

SK has been in operation since April 1996. In 2020, SK started the SK-Gd phase, in which 13 tons of gadolinium sulfate octahydrate were added to the water in the detector, achieving a concentration of 0.01% Gd by mass. SK-Gd is characterized by an improved sensitivity to low energy electron anti-neutrinos by efficiently detecting the products of Inverse Beta Decay (IBD) interactions. The capture of neutrons resulting from IBD by gadolinium has a cross section 10,000 greater than the capture in Hydrogen and emits an 8 MeV gamma-ray cascade, instead of a single 2.2 MeV gamma-ray. In 2022, with an extra loading of 26 tons of gadolinium sulfate octahydrate to the water, SK-Gd started a second phase with a concentration of 0.03% Gd by mass.

SK-Gd extended the purposes of the experiment, allowing the detection of neutrinos from diffuse supernova neutrino background, reactors and pre-supernova stars.

2. Pre-Supernova (Silicon Burning) Stars

The neutrino emission increases significantly as a massive star ($M > 8M_{\odot}$) approaches the core collapse supernova (CCSN). After ignition of Carbon burning these stars are classified as neutrino-cooling star or pre-supernova (preSN) star. The burning stage preceding the CCSN is the silicon burning phase and it is expected to last for a few days. At this stage, neutrino luminosity can reach $10^{12}L_{\odot}$, while the photon luminosity $10^{5}L_{\odot}$.

The neutrino production in preSN stars is mainly from electron-positron annihilation, generating neutrinos and anti-neutrinos of every flavors. Nuclear weak processes such Beta Decay dominate near the core-collapse. Figure 2 shows the evolution of the neutrino luminosity and average energy as a $15M_{\odot}$ star approaches the CCSN for different preSN models.

A potential detection of preSN neutrinos will be an un-affected observation of the interior of stars and have many benefits such as the understanding the physical processes leading to CCSN,

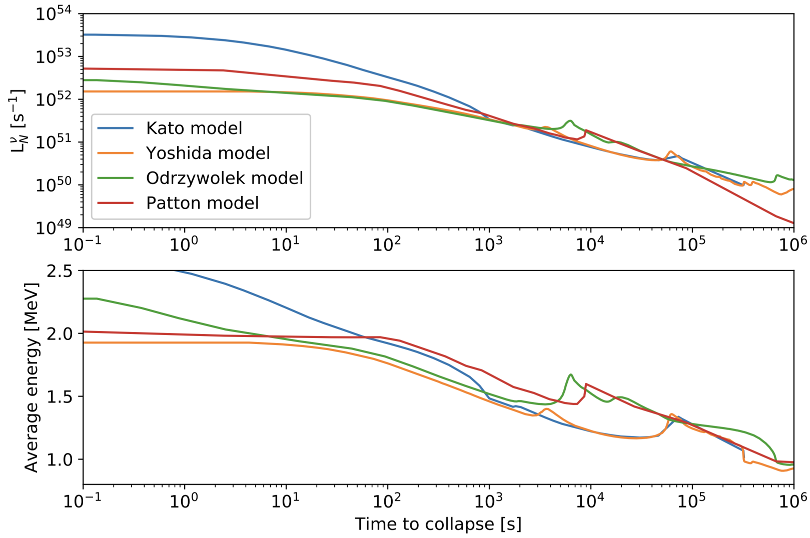
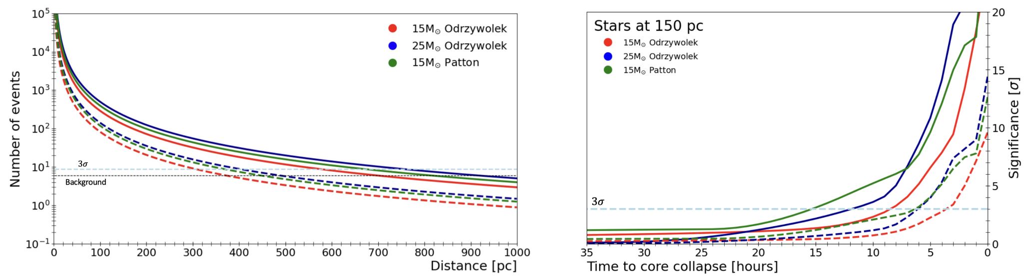


Figure 2: Number luminosity (top) and average energy of $\bar{\nu}_e$ (bottom) as star approaches core collapse. Reproduced from [1].

evidence to neutrino mass ordering, and give an early warning for CCSN, since preSN neutrinos are emitted over a very long timescale before the supernovae.

3. Sensitivity to Pre-Supernova Neutrinos (0.03% Gd)

SK-Gd can potentially detect preSN $\bar{\nu}_e$ via IBD, selecting the resulting positron and neutron from the interaction based on their temporal/spacial correlation. Boosted Decision Tree is also used for selection [2]. The main background sources for preSN neutrinos are reactor neutrinos, geoneutrinos, radioactive decays and fake IBD events (accidental coincidences).



(a) **(b)**

Figure 3: (a) Expected number of IBD preSN events as a function of the distance and (b) evolution of the detection significance level as a massive star approaches core-collapse (d = 150 pc) in SK-Gd with 0.03% Gd. Solid lines show normal neutrino mass hierarchy and dashed lines show inverted neutrino mass hierarchy. For models Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611 and Patton, et al 2017 ApJ 851 6.

Figure 3a shows the expected number of $\bar{\nu}_e$ events for different preSN models as a function of the distance and Figure 3b shows the evolution of the detection significance for stars at 150 parsecs. The detection significance evolves as the star approaches the core-collapse, exceeding 3σ from 9 to

16 hours before collapse for the different preSN models (following normal neutrino mass ordering) at 150 parsecs and progenitor mass of $15M_{\odot}$.

3.1 Pre-Supernova Alert System

An early warning system for supernovae based on the search for preSN neutrinos is running in SK since October 2021 [2]. The system is integrated to the independent trigger Wide-band Intelligent Trigger (WIT) [3]. Data is received by the system immediately after acquisition and fast reconstruction online. Figure 4 shows the expected warning hours of the system. For the most optimistic model for Betelgeuse (with $15M_{\odot}$ at 150 parsecs, following the model Patton, et al 2017 ApJ 851 6), the early warning is approximately 15 hours before the core collapse.

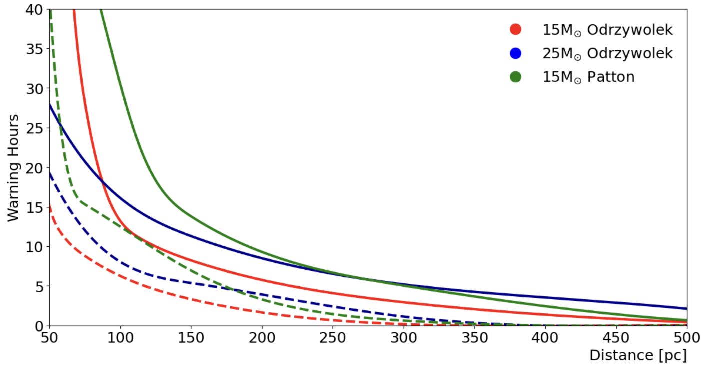


Figure 4: Expected warning hours as function of distance for a 3σ detection by the preSN alert system for Super-Kamiokande with 0.03% Gd. Solid (dashed) lines show normal (inverted) neutrino mass hierarchy. For models Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611 and Patton, et al 2017 ApJ 851 6.

The Kamioka Liquid-scintillator Antineutrino Detector (KamLAND) experiment, which is also located at the Kamioka mine in Japan, has a preSN alarm running since 2015 [4]. SK and KamLAND launched a combined preSN alert system in 2023, using local real-time results from both experiments to calculate a common significance level. The combined system is accessible at [5].

References

[1] C. Kato *et al.*, *Theoretical Prediction of Presupernova Neutrinos and Their Detection*, *Ann.Rev.Nucl.Part.Sci.* **70** 121-145 (2020).

[2] L. N. Machado *et al.*, *Pre-supernova Alert System for Super-Kamiokande*, *Astrophys. J.* **935**, 1, 40 (2022).

[3] G. Carminati *et al.*, *The new Wide-band Solar Neutrino Trigger for Super-Kamiokande*, *Physics Procedia* **61**, 666-672 (2015).

[4] K. Asakura *et al.*, *KamLAND Sensitivity to Neutrinos from Pre-Supernova Stars*, *Astrophys. J.* **818**, 91 (2016).

[5] KamLAND Collaboration and Super-Kamiokande Collaboration. *Combined pre-supernova alarm system* *https://www.lowbg.org/presnalarm*. Accessed 01 02 2024.