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

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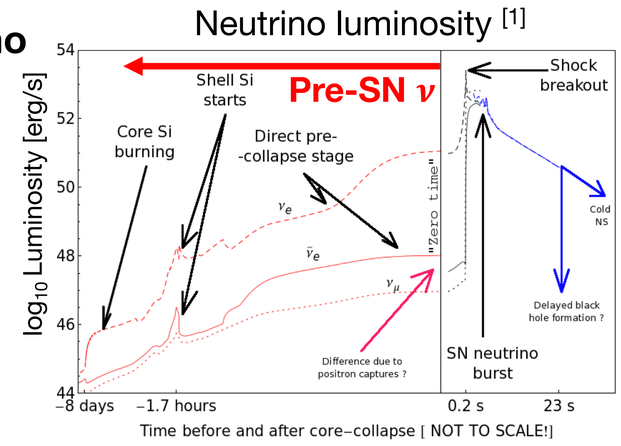
1. Introduction

Pre-supernova (pre-SN) neutrino

These neutrinos are generated by massive star ($M \gtrsim 8M_{\odot}$) at the end of stelar evolution.

Observation of pre-SN neutrinos
- → insight into stellar evolution
- → hints toward understanding neutrino mass ordering
- → Early warning to SN (Pre-SN alarm)

Neutrino luminosity [1]



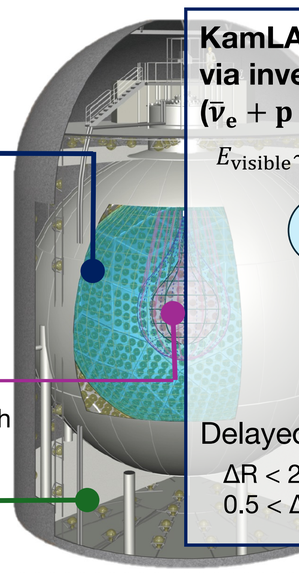
Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND)

1000m depth
×10⁻⁵ muon flux

1000t liquid scintillator (LS) detector
Dodecan (80%),Psedocumene(20%), PPO (1.36g/l)
with 1325 17-inch PMTs + 554 20-inch PMTs

Inner balloon
Xe loaded LS for 0νββ search
Volume cut (r=1.92 m)

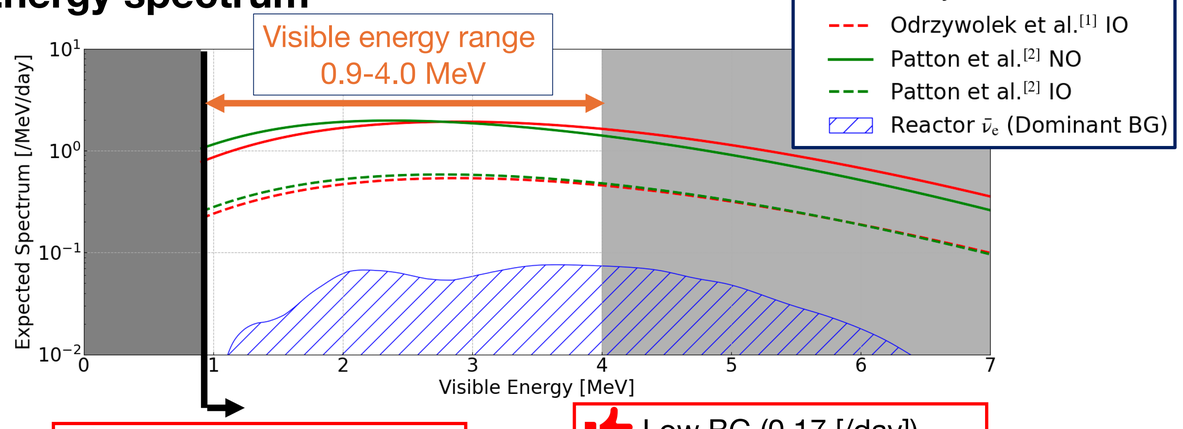
Pure water
For muon veto



KamLAND detects pre-SN $\bar{\nu}_e$ via inverse beta decay
($\bar{\nu}_e + p \rightarrow e^+ + n$)
$E_{visible} \sim E_{\bar{\nu}_e}$ -0.78 MeV

Prompt signal: Positron, Annihilation
0.512 MeV γ
Delayed coincidence (DC)
ΔR < 200 cm
0.5 < ΔT < 1000 μs
Delayed signal: Neutron capture
2.2 MeV γ

Energy spectrum



Low energy threshold $E_{\bar{\nu}_e}$ >1.8 MeV

Low BG (0.17 [/day]) with DC scheme

KamLAND has unique sensitivity to Pre-SN $\bar{\nu}_e$

Current online Pre-SN alarm system at KamLAND (since 2015) [3]

- The system is based on the significance of statistical excess from BG rate. (Rate analysis)
- Time window is 24 hour.
- BG rate is the average one over last 90 days.

Motivation

In order to improve alarm sensitivity,

1. **Incorporating time profile**
2. **Combining with Super-Kamiokande**

→ **This poster shows improved sensitivity**

2. Incorporating time profile (Rate+Shape analysis)

Concept of alarm system with time profile of pre-supernova neutrinos [4]

Likelihood function

$$L(t,\{t_i\}|\mathrm{BG}+\mathrm{Signal}) = \underbrace{\mathrm{Pois}\big(n(t), s_{\exp}+b_{\exp}\big)}_{\text{rate term}} \underbrace{\prod_{i=1}^{n} \mathrm{Prob}(t_i|\mathrm{BG}+\mathrm{Signal})}_{\text{shape term}}$$

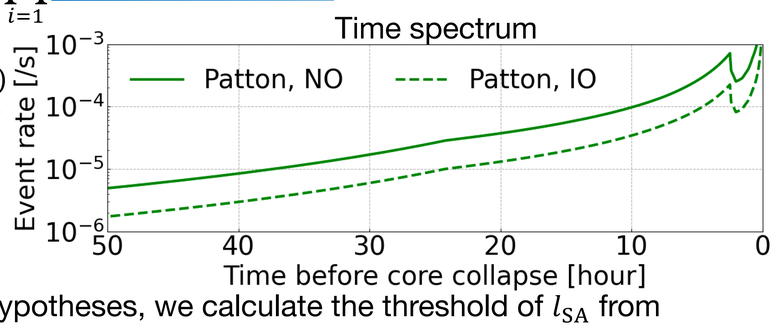
$\{t_i\}$: event time array ($\subset [t, t+200\ \mathrm{hour}]$)
(n = number of $\{t_i\}$ elements)

$$L(t,\{t_i\}|\mathrm{BG}) = \underbrace{\mathrm{Pois}\big(n(t), b_{\exp}\big)}_{\text{rate term}} \underbrace{\prod_{i=1}^{n} \mathrm{Prob}(t_i|\mathrm{BG})}_{\text{shape term}}$$

Log likelihood ratio

$$l_{\mathrm{SA}}(t,\{t_i\}) = \log \frac{L(\{t_i\}|\mathrm{BG}+\mathrm{signal})}{L(\{t_i\}|\mathrm{BG\ only})}$$

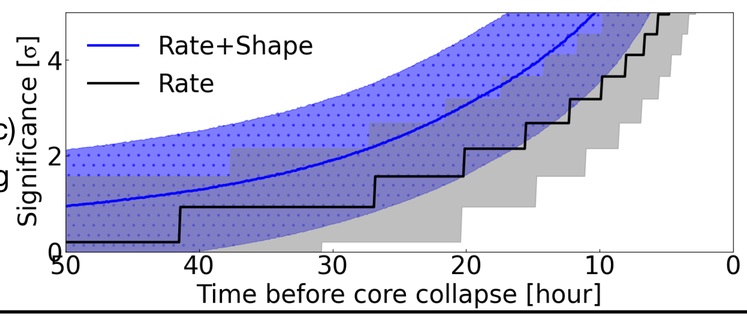
Time spectrum



To distinguish between BG and BG+Signal hypotheses, we calculate the threshold of l_{SA} from event time array using toy MC simulation.

Sensitivity

Target star : Betelgeuse-like star (15 $M_{\odot}$, 150 pc)
Model: Patton model with normal mass ordering



Alarm sensitivity is improved.

Check of the robustness for model dependence

Star → Pre-SN $\bar{\nu}_e$ (**Observed model**)

Alarm system (Rate+Shape analysis)
Observed time spectrum ⟷ Reference time spectrum (**Reference model**)
How well does observed spectrum shape replicate reference one?
→ Alarm sensitivity is evaluated.

Warning time [hour] (Expected significance > 3σ)

		Rate+Shape Reference model: Patton NO	Rate+Shape Reference model: Patton IO	Rate
Observed model	Patton NO	**20.4**	**20.2**	12.2
	Patton IO	**7.3**	**7.3**	2.4

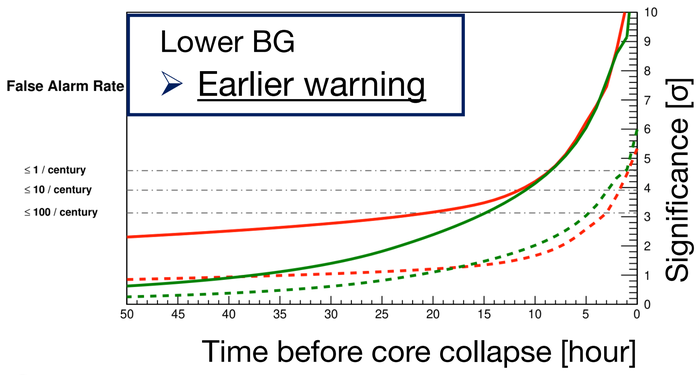
Rate+Shape analysis has higher sensitivity than Rate analysis.

3. Combining with Super-Kamiokande

This analysis uses **only rate**.

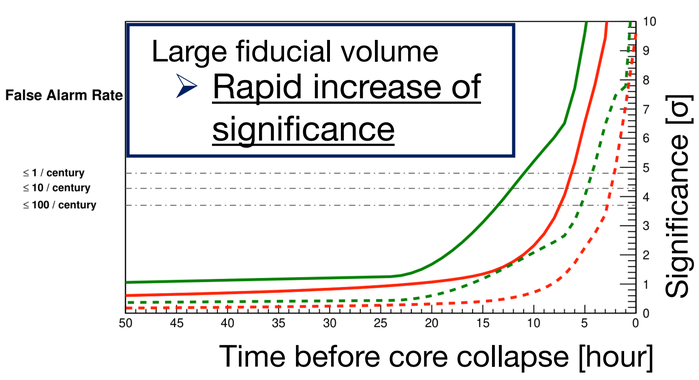
KamLAND

Lower BG
➢ Earlier warning



SK

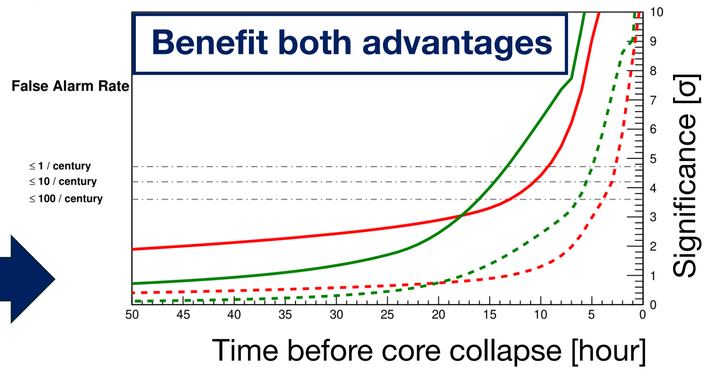
Large fiducial volume
➢ Rapid increase of significance



Combined of KamLAND & SK

The alert system is triggered based on BG rate of both KamLAND and SK

Benefit both advantages



Super-Kamiokande (SK)

- SK is 22.5kt water Cherenkov detector.
- 0.03% of gadolinium was loaded. (SK-Gd)

➢ **SK can detect pre-SN $\bar{\nu}_e$**
➢ Online pre-SN alarm system has been started since 2021. [5]

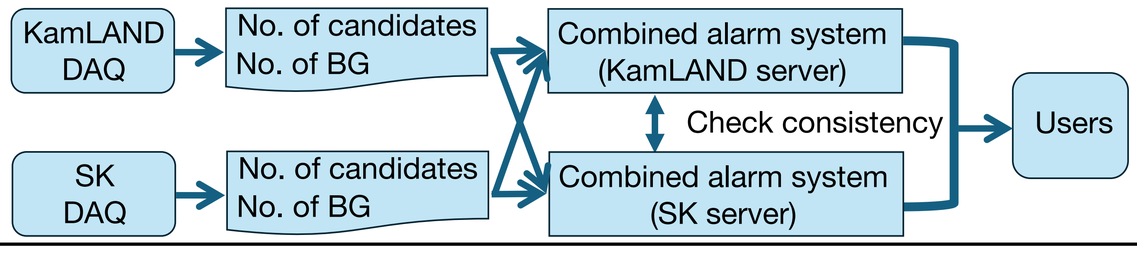
Warning time [hour]
(Expected significance corresponding to FAR < 1/century)

model	Mass ordering	KamLAND	SK	Combined
Odrzywolek	NO	7.4	6.3	**8.7**
	IO	0.4	2.1	**2.6**
Patton	NO	7.3	10.9	**12.9**
	IO	0.7	4.3	**4.8**

Combined alarm provides earlier warning than individual alarms.

Online combined alarm system (https://www.lowbg.org/presnalarm/)

- Running in both KamLAND and SK side (redundancy system)
- BG: Averaged event number over a past period (KamLAND 90days, SK: 30days)
- Total latency time ~ 6 min
- Output every 5 minutes
- Link GCN circular



4. Summary and prospect

- ✓ In order to **improve alarm sensitivity**, this poster presents two approaches.
- ✓ We develop an earlier-issued alarm which use **time spectrum** than the current alarm.
- ✓ In order to **improve alarm sensitivity**, We develop combined alarm system of KamLAND and SK. (using only rate)
- ✓ The combined alarm system is running.

- ☐ Study of **estimation the core-collapsed time**
- ☐ Development of rate+shape(time)+shape(**energy**) alarm system
- ☐ Submitting of paper about combined pre-SN alarm system

Reference
[1] Odrzywolek et al.,APPS B B41 (2010) 1611
[2] Kelly M. Patton et al (2017) ApJ 851 6
[3] K. Asakura et al. Astrophys.J. 818 (2016) 1, 91
[4] A. Sheshukov et al JCAP12(2021)053
[5] L. N. Machado *et al* (2022) ApJ 935 40