超新星前兆ニュートリノアラームの研究

Development of Pre-Supernova Alarm System

Keita Saito

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第10回 超新星ニュートリノ研究会

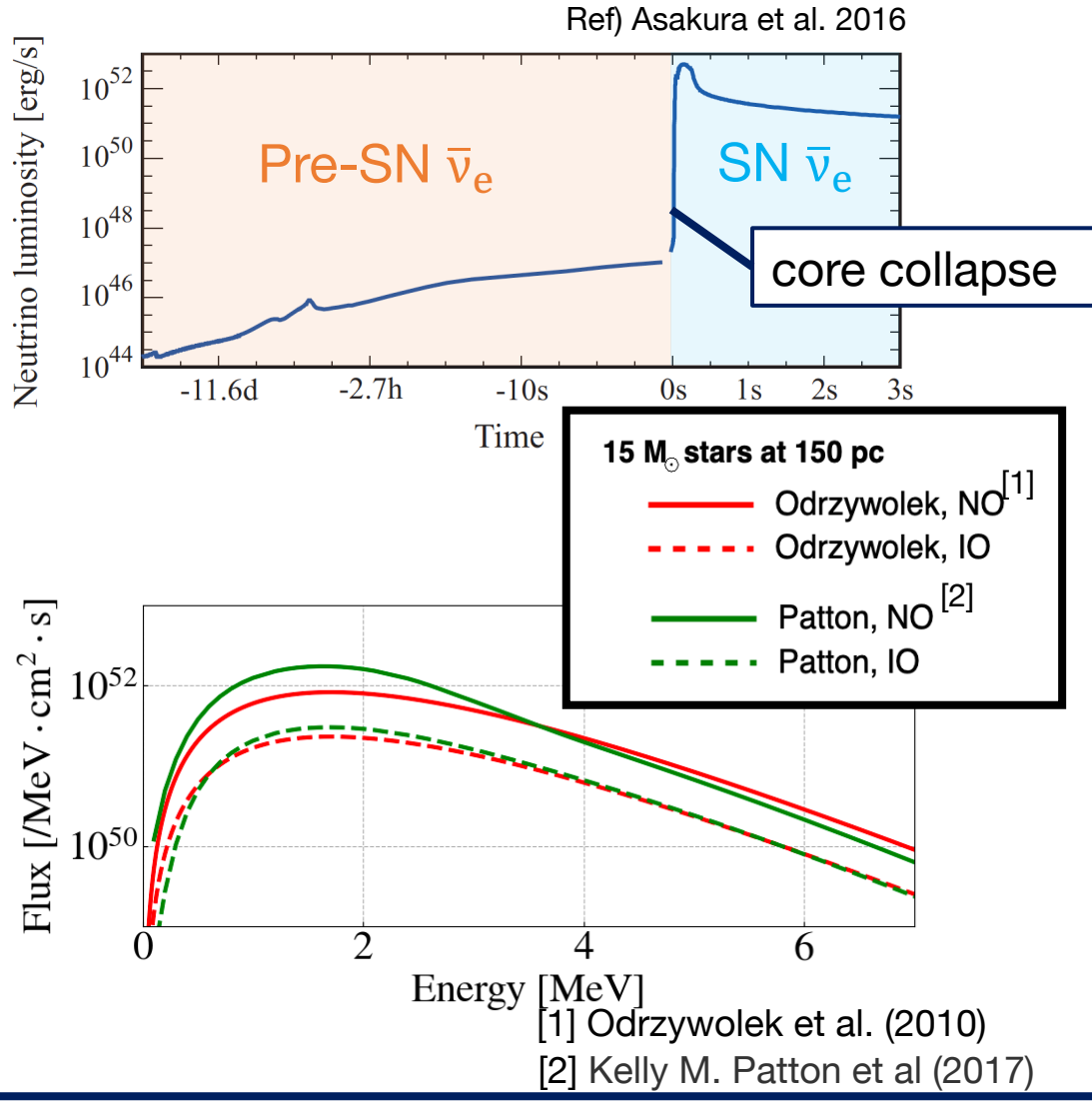
Contents

1. Introduction

Pre-supernova (pre-SN) neutrino

- All flavor neutrinos are predominantly emitted in neutrino cooling phase during the last stage of massive ($M > 8\ M_\odot$) stars.
- Main processes are
  - Thermal pair production: $e^+e^- \rightarrow \nu\bar{\nu}$
  - Weak interactions
- The observation of pre-SN neutrinos provides
  - Insight into stelar evolution
  - Hints toward understanding of the neutrino mass ordering
  - **Early alarm system before core collapse**
- KamLAND and Super-Kamiokande are **capable to detect the neutrinos from nearby stars**.
  - **Betelgeuse** (15 $M_\odot$, 150pc) etc.

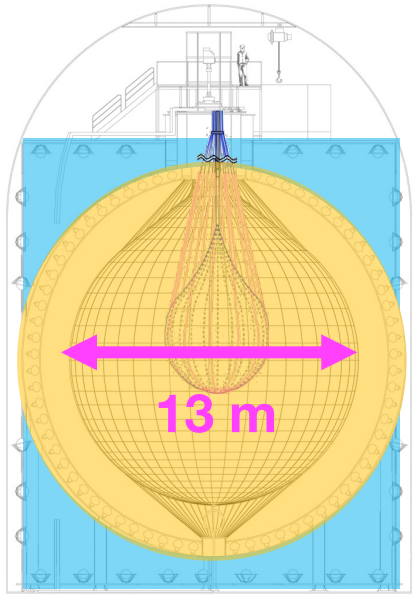
Ref) Asakura et al. 2016



[1] Odrzywolek et al. (2010)
[2] Kelly M. Patton et al (2017)

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector (since 2002)



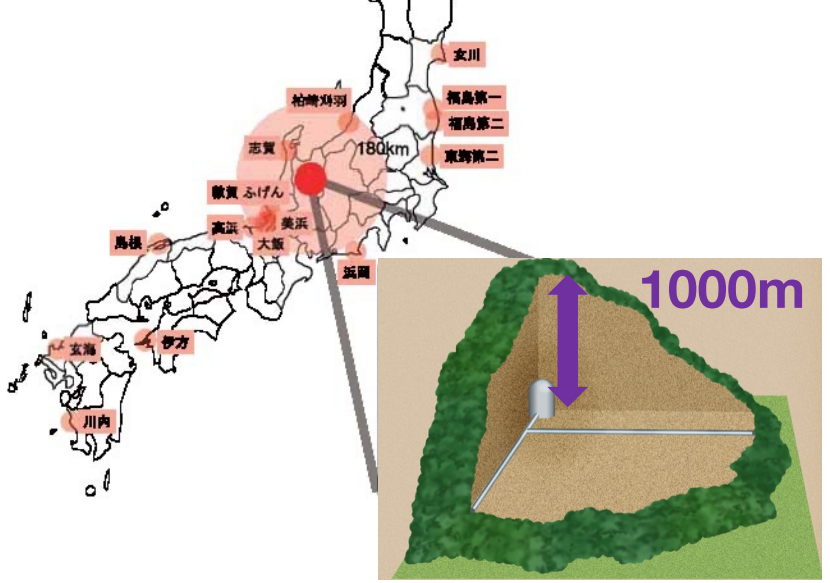
Inner detector (neutrino detector)

1kt liquid scintillator

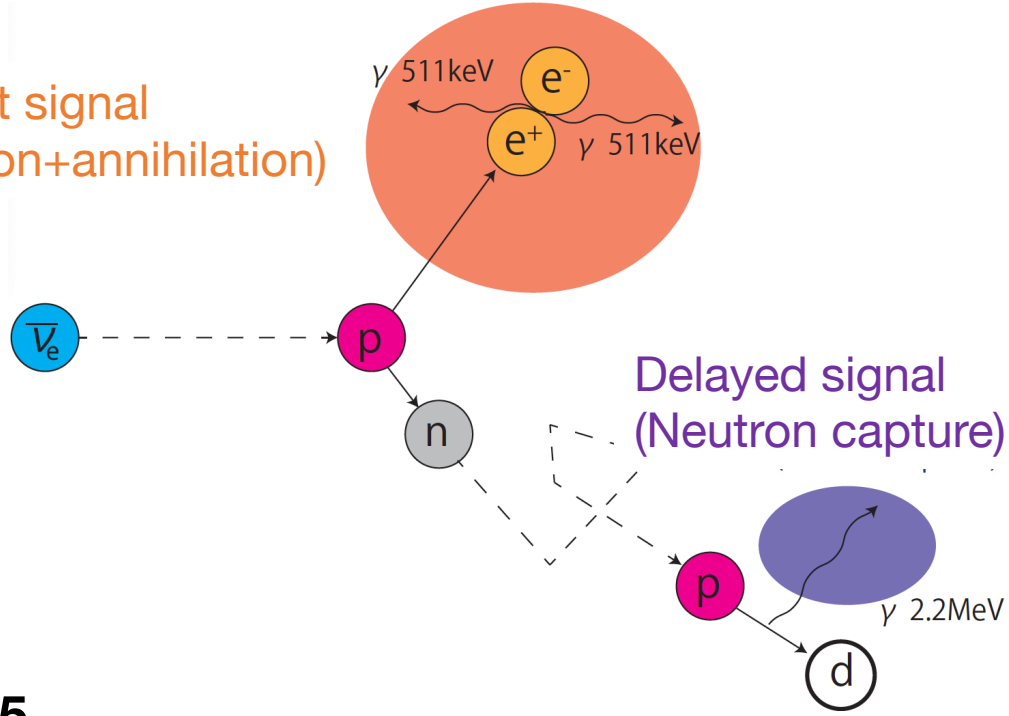
1325 17inch + 554 20inch PMTs

Outer detector (veto detector)

Water Cherenkov detector



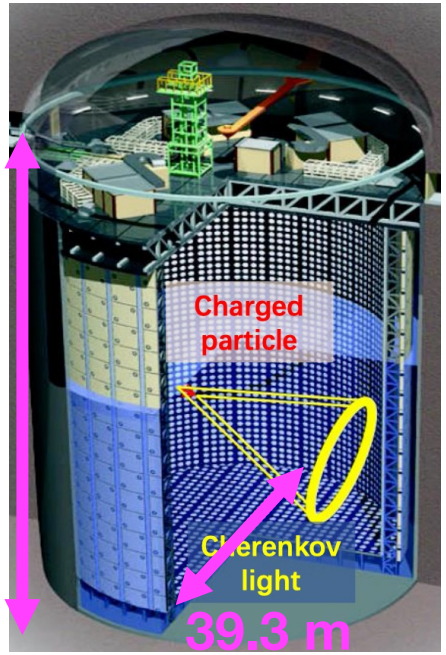
- KamLAND detects pre-SN $\bar{\nu}_e$ via inverse beta decay (IBD, $\bar{\nu}_e + p \rightarrow e^+ + n$).
- Low energy threshold: $E_{\bar{\nu}_e}$ >1.8 MeV
- Low background (Main BG: reactor $\bar{\nu}_e$)
  - Delayed coincidence of prompt and delayed signal



- **KamLAND has unique sensitivity to pre-SN $\bar{\nu}_e$**
- **Pre-SN alarm system has been launched since 2015**

Ref) Asakura et al. 2016

Super-Kamiokande



Super-Kamiokande (SK) is a water Cherenkov neutrino detector in Kamioka mine. (since 1996)

Inner detector (neutrino detector)

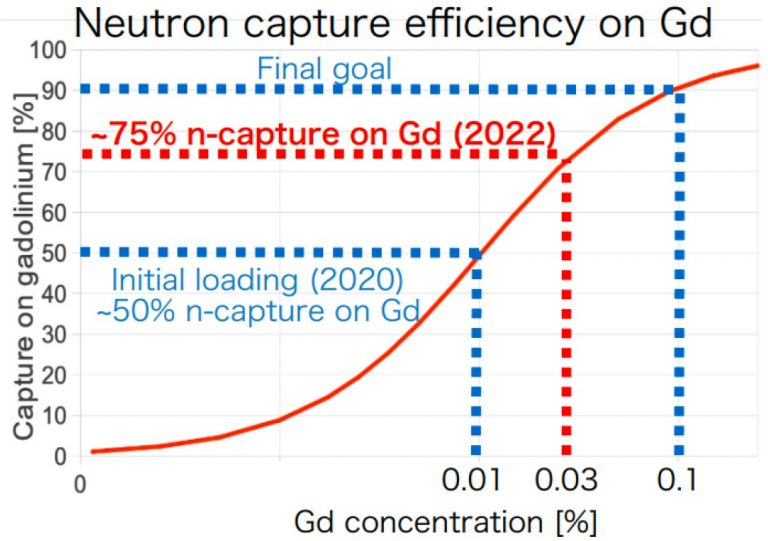
22.5 kt water Cherenkov detector

with 11000 20inch PMTs

Outer detector (veto detector)

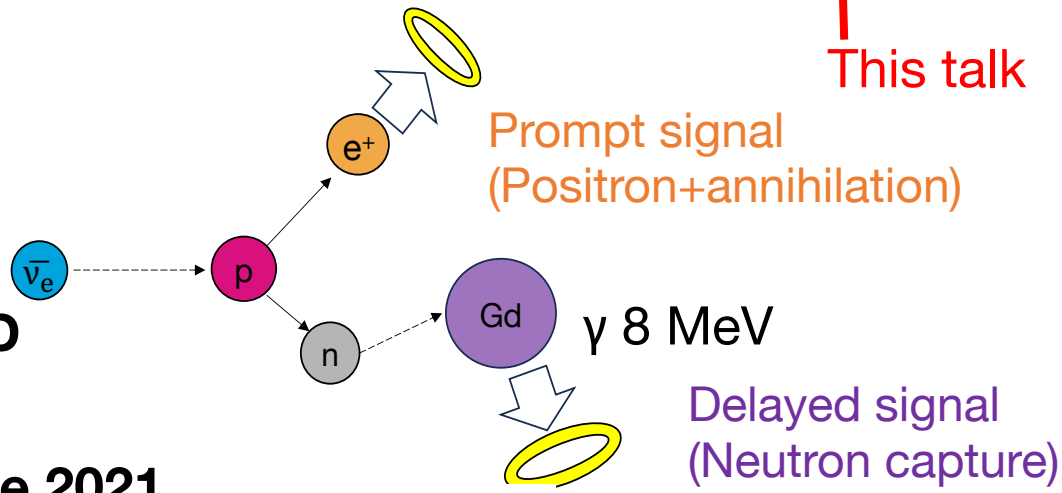
Water Cherenkov detector

with 1885 8inch PMTs



SK-Gd experiment

- Gadolinium (Gd) is loaded into water.
- SK is capable to capture neutrons.
  - **SK is capable to detect pre-SN $\bar{\nu}_e$ through IBD**
    (Main BG is reactor $\bar{\nu}_e$)
  - **Pre-SN alarm system has been launched since 2021**



Ref) Machado et al. 2022

2. Combined pre-SN alarm system

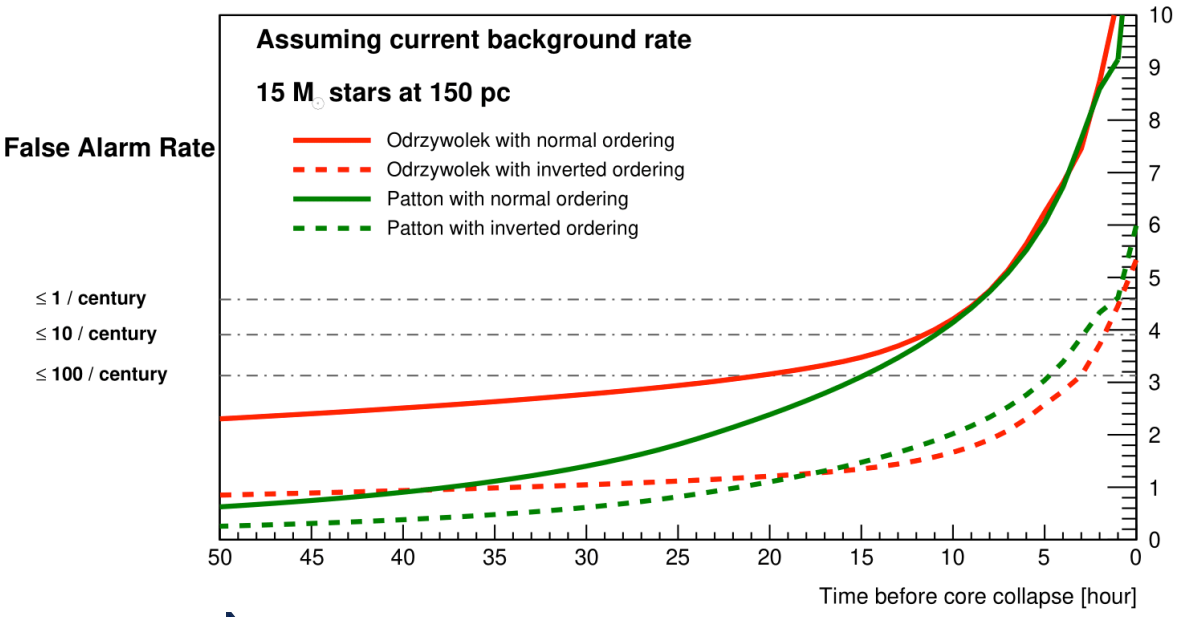
Combined pre-SN alarm system

- Both KamLAND and SK alarm system is based on significance of **statistical excess of BG number**.

KamLAND

- Lower BG rate

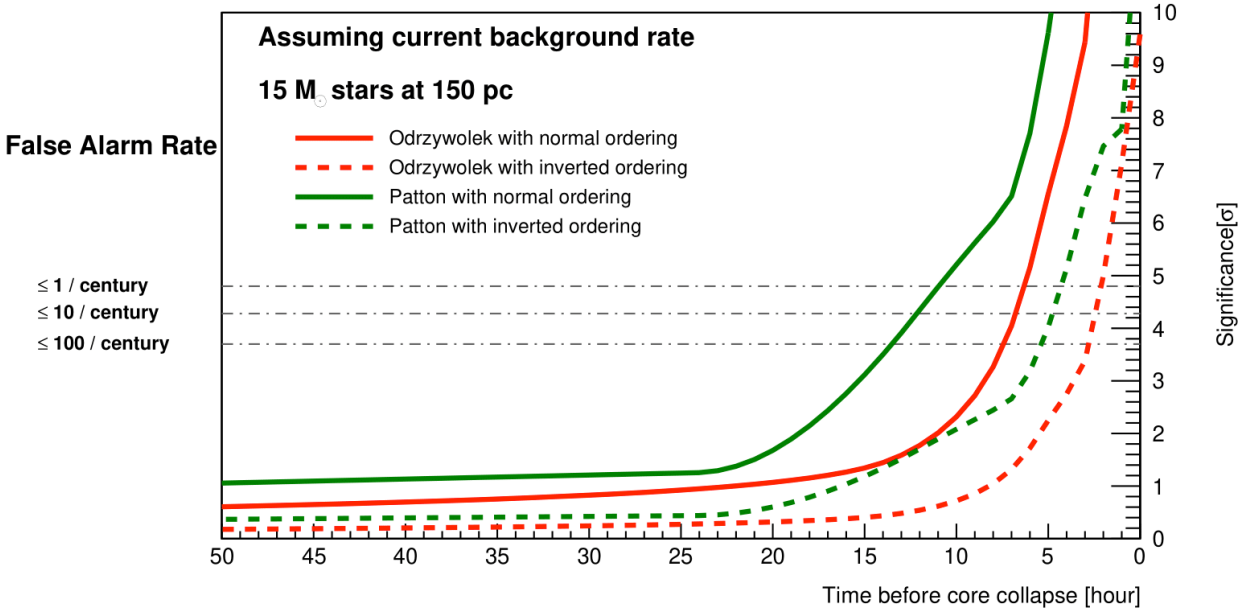
Earlier warning to supernovae



SK

- Larger target mass

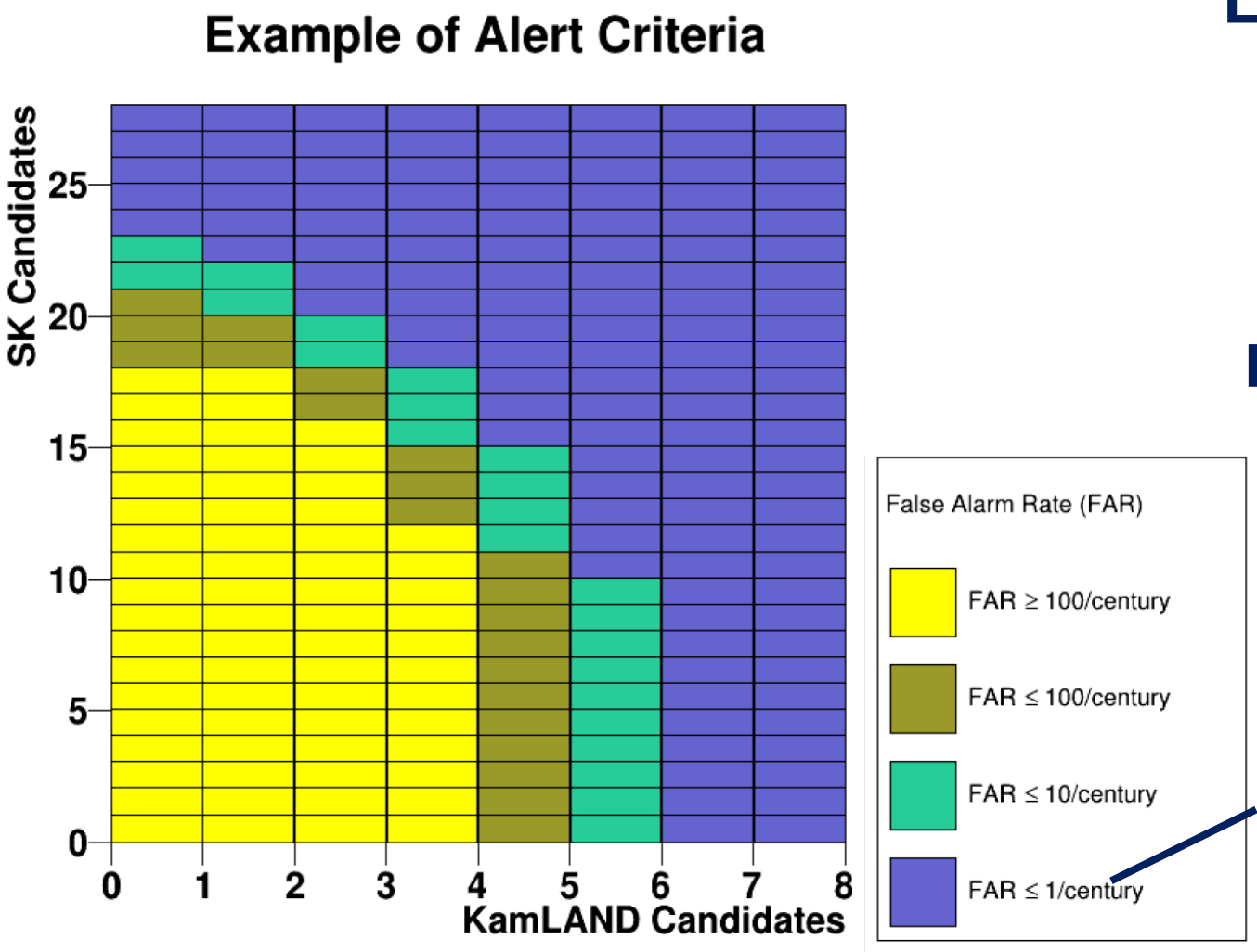
Significance is increased rapidly



Combined alarm system with KamLAND and SK is expected to benefit from advantages of both detectors and improve the alarm sensitivity.

Concept of combined alarm

- The alarm system is triggered based on statistical excess of **BG level of both KamLAND and SK**.



Likelihood function

$$L\left(n_{\mathrm{KL}}^{\mathrm{obs}}, n_{\mathrm{SK}}^{\mathrm{obs}}\right) = \mathrm{Pois}(n_{\mathrm{KL}}^{\mathrm{obs}}, n_{\mathrm{KL}}^{\mathrm{BG}}) \times \mathrm{Pois}(n_{\mathrm{SK}}^{\mathrm{obs}}, n_{\mathrm{SK}}^{\mathrm{BG}})$$

n^{obs}: number of candidates

n^{BG}: number of expected BG

False alarm rate (FAR)

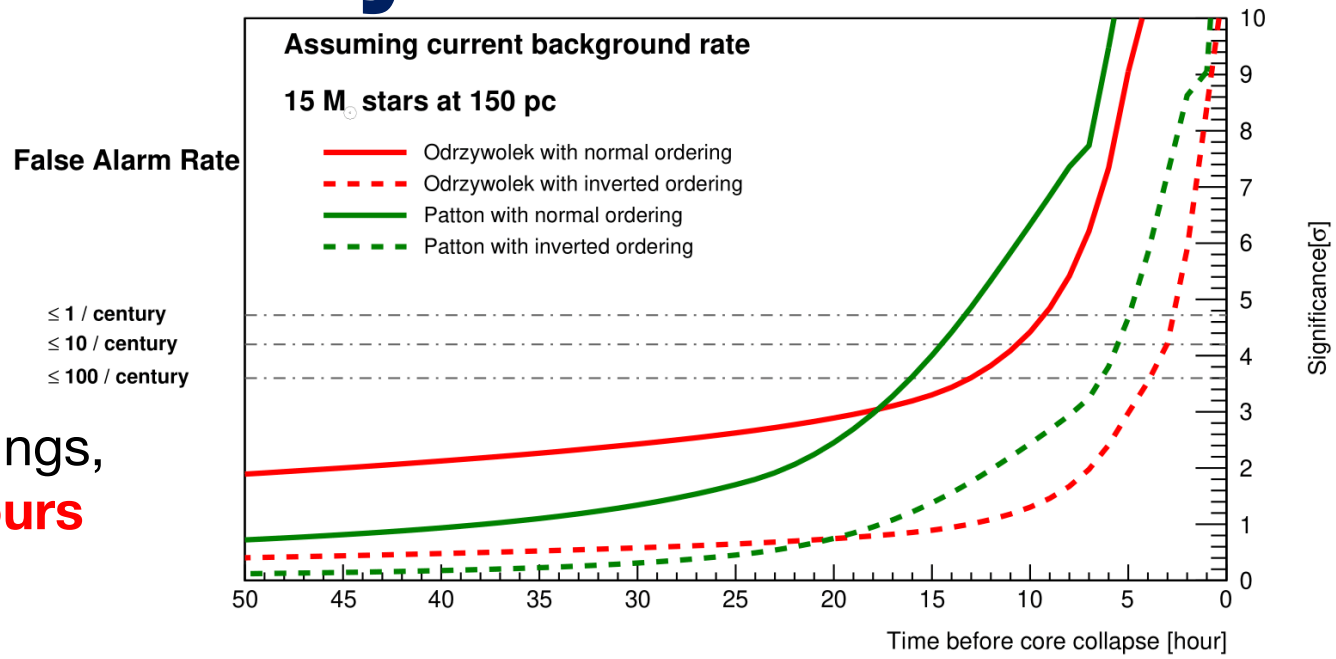
- Frequency of false positive alarms based on BG number
- It is calculated with toy MC simulation assuming only BG

The system provides warning when the combinations of $n_{\mathrm{KL}}^{\mathrm{obs}}$ and $n_{\mathrm{SK}}^{\mathrm{obs}}$ are in **blue region** (≦ 1 FAR/century).

Combined alarm sensitivity

- Combined alarm system provides **earlier warning time** than individual alarms.

- For signals from any models or mass orderings, combined alarm can be issued **at least 2.6 hours before core collapse**.



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

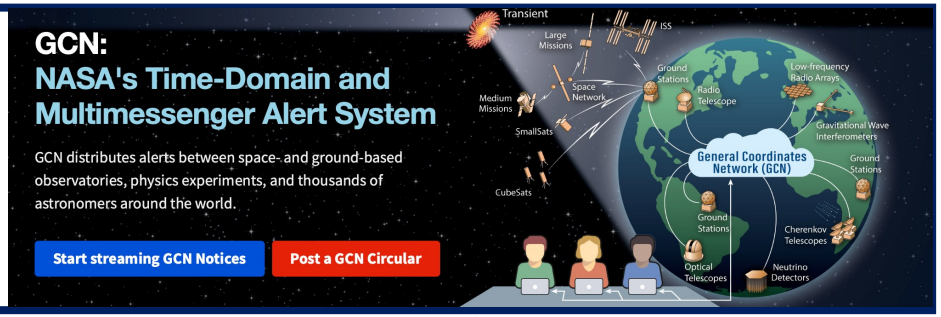
model	Mass ordering	KamLAND	SK	Combined
Odrzywolek	NO	7.4	6.3	**8.7**
	IO	0.4	2.1	**2.6**
Patton	NO	7.3	10.9	**12.9**
	IO	0.7	4.3	**4.8**

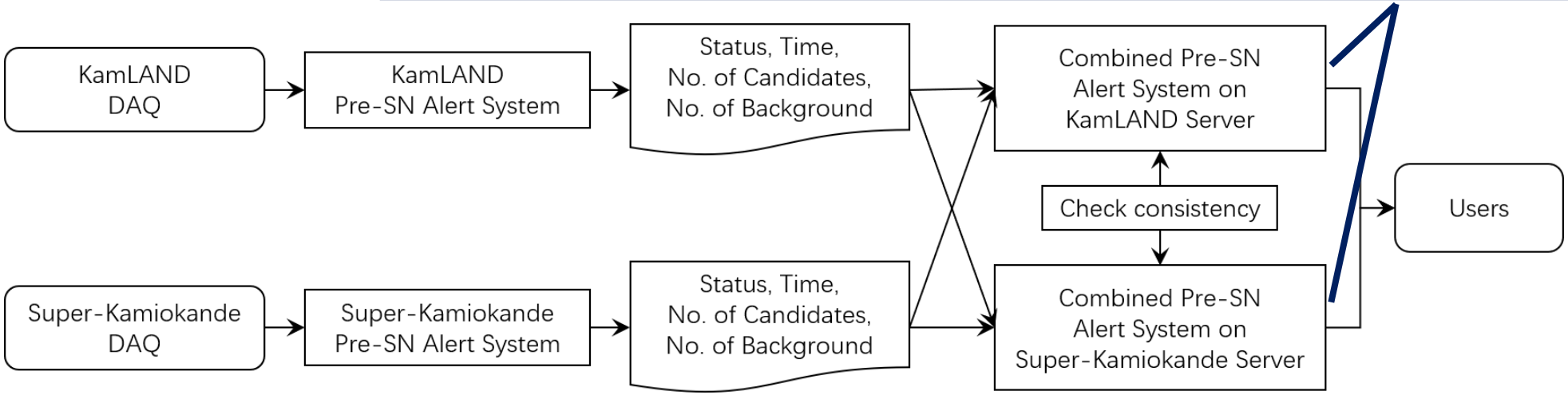
Online combined alarm system (since 2023)

- Combined alarm system is **running in both KamLAND and SK side (redundancy system).**
- BG number is average one over a past period. (KamLAND: 90 days, SK: 30 days)
- Total latency time is approximately **6 minutes**.
- The system outputs **every 5 minutes**.

If FAR ≦ 1/century,

An alarm will be sent
Gamma-ray Coordinate Network.





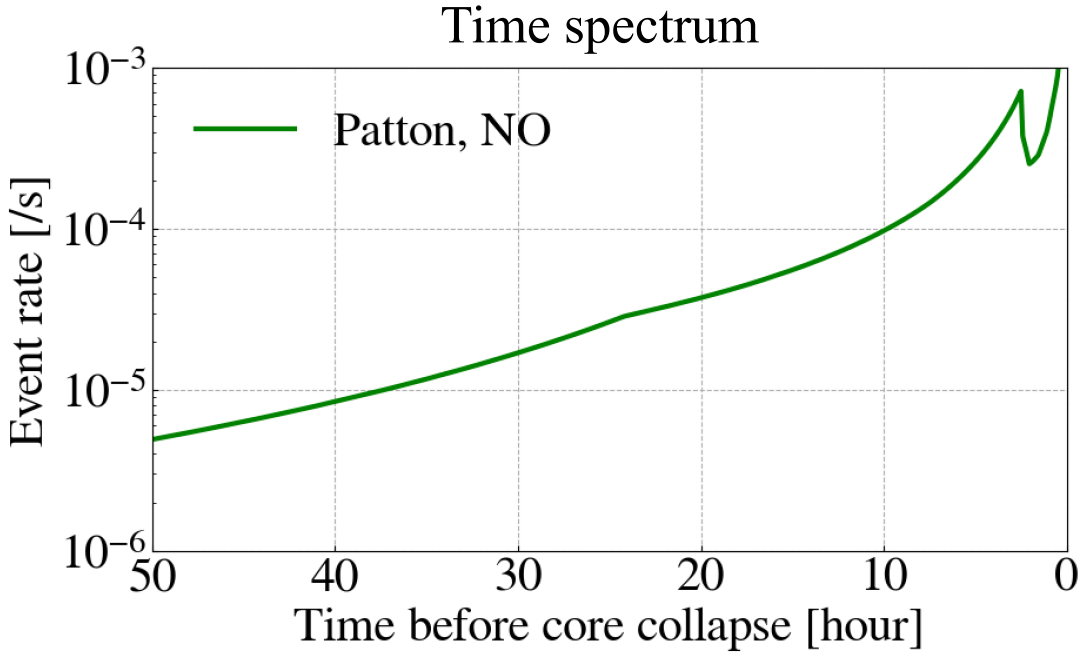
3. Rate+Shape analysis

Rate+Shape analysis

- Combined pre-SN alarm has higher sensitivity than individual detectors.
- In order to **further enhance alarm sensitivity**,

Rate analysis (current alarm system)

- Based on BG rate
- $L(n^{\mathrm{obs}}) = \mathrm{Pois}(n^{\mathrm{obs}}, n^{\mathrm{BG}})$



Rate+Shape analysis

- Based on BG rate and **time spectrum**
- $L(n^{\mathrm{obs}}, \{t_i\}) = \mathrm{Pois}(n^{\mathrm{obs}}, n^{\mathrm{BG}}) \prod_{i=1}^{n^{\mathrm{obs}}} \mathrm{Prob}(t_i)$

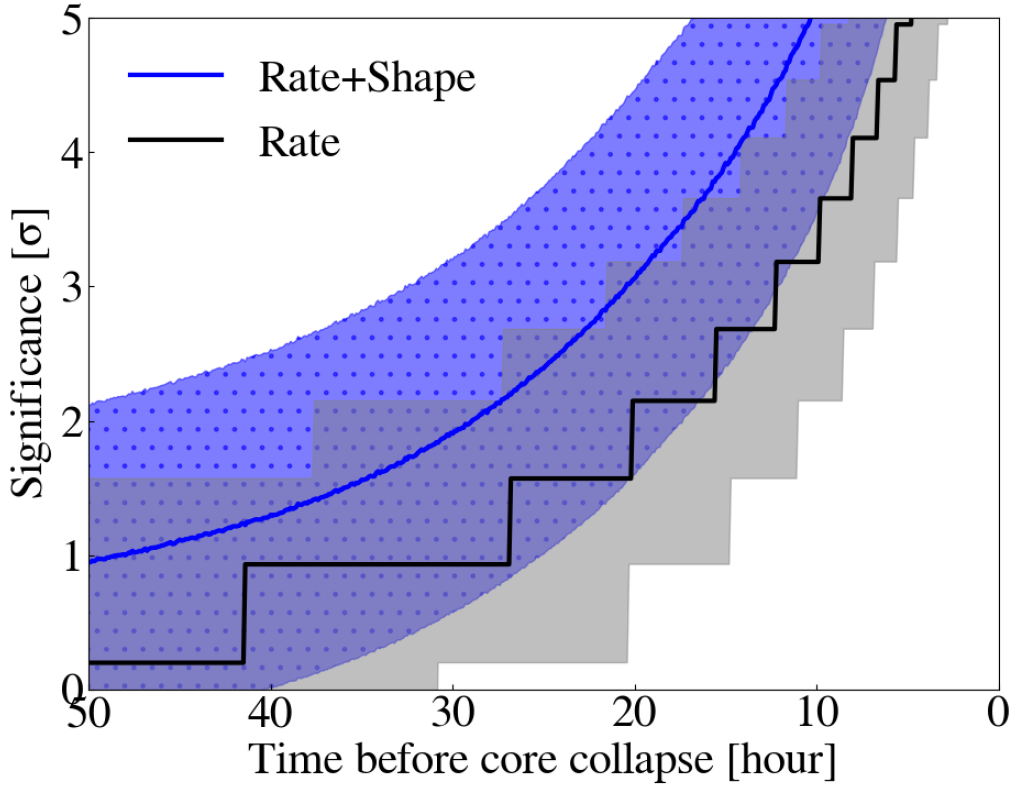
$\{t_i\}$: event time array

(number of $\{t_i\}$ elements = n^{obs})

We shows the alarm sensitivity based on the simulation assumed KamLAND.

Alarm sensitivity

Alarm sensitivity at KamLAND
(detection probability=50%±1σ)



Target star

Betelgeuse ($15M_{\odot}$, 150 pc)

Model

Patton model, Normal mass ordering

Detection probability

The proportion of results exceeding the significance

Alarm sensitivity is improved.

Summary and prospect

Summary

- KamLAND and SK have unique sensitivities to pre-SN neutrinos.
  - **Pre-SN early warning system**

- In order to **improve alarm sensitivity**, We develop combined alarm system of KamLAND and SK.
  - The combined alarm system has been running and open to public. (https://www.lowbg.org/presnalarm/)

- Rate+Shape analysis has **higher alarm sensitivity** than Rate analysis (current alarm).

Prospect

Combined alarm system

- We will submit **paper** of combined pre-SN alarm system.

Rate+Shape analysis

- Check of **the robustness** for this model depending system.
- Study of **estimation of core collapsed time**.
  - Core collapsed time is required for calculation of the likelihood function.
- Development of rate+shape(time)+shape(**energy**) alarm system.