Combined Pre-supernova Alert System with KamLAND and Super-Kamiokande

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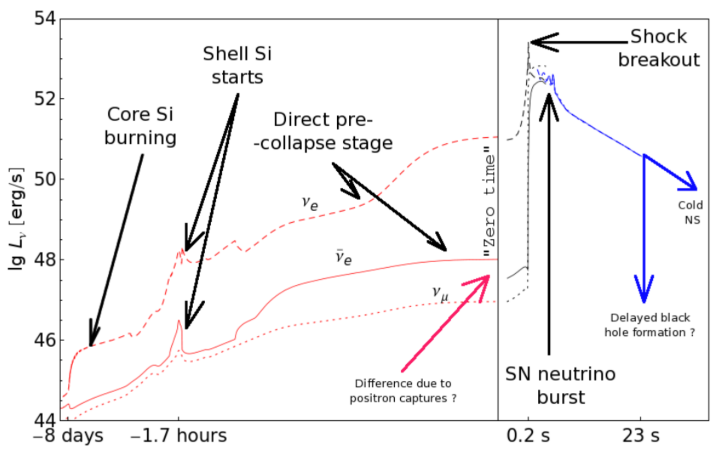
INSS24

1. Pre-Supernova Neutrinos



Neutrino luminosity as a function of time before and after core-collapse [1].

Early warning of a supernova

- Early warning of a SN would be helpful for getting ready for SN neutrinos and gravitational wave observations

Pre-supernova (Pre-SN) neutrinos

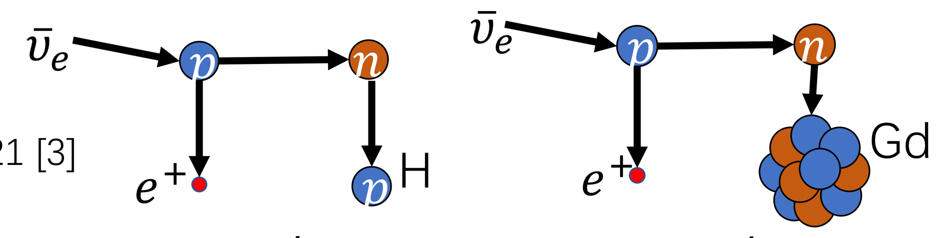
- Before core-collapse, the progenitor emits all flavors of neutrinos increasingly with mounting energies.
- Starting at the silicon burning phase, a significant fraction of electron anti-neutrinos ($\bar{\nu}_e$) exceed inverse beta decay (IBD) threshold
- Potentially detectable, thus can be early warnings of a SN

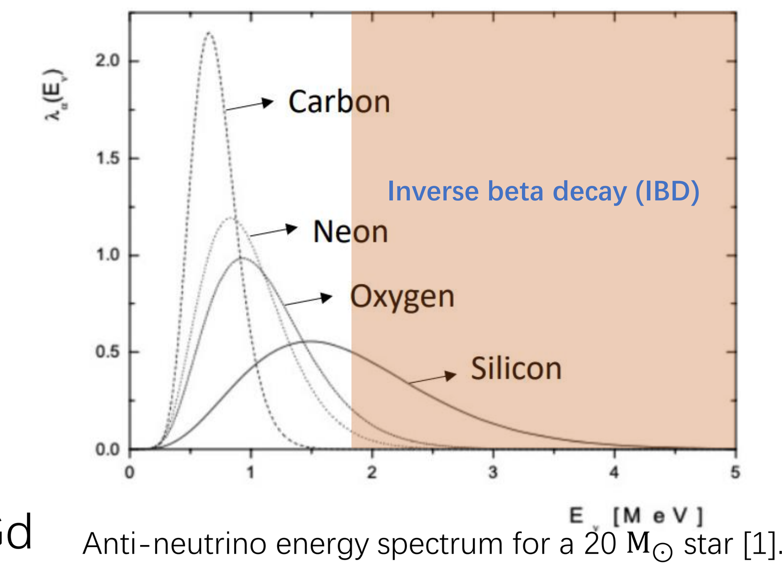
Pre-SN monitors

- KamLAND pre-SN monitor online in 2015 [2]
- Super-Kamiokande (SK) also set a pre-SN monitor in 2021 [3]

COMBINED pre-SN alert with SK and KamLAND

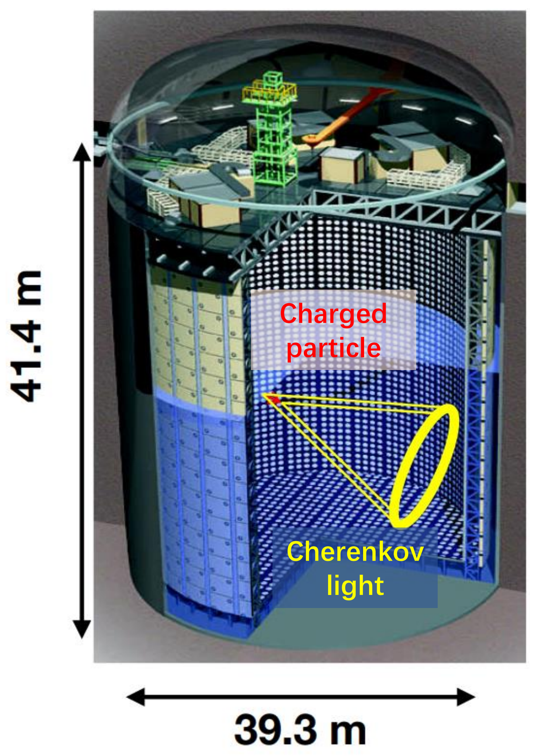
- Developed to improve the sensitivity to pre-SN neutrino signals





Anti-neutrino energy spectrum for a 20 $M_\odot$ star [1].

2. Pre-SN Neutrinos in SK



Super-Kamiokande [4]

- 50-kton water Cherenkov detector in the Kamioka mine

Inner detector

- Cylinder volume (r=16.9m, h=36.2m) with pure water
- ~11,000 20-inch PMTs

Outer detector

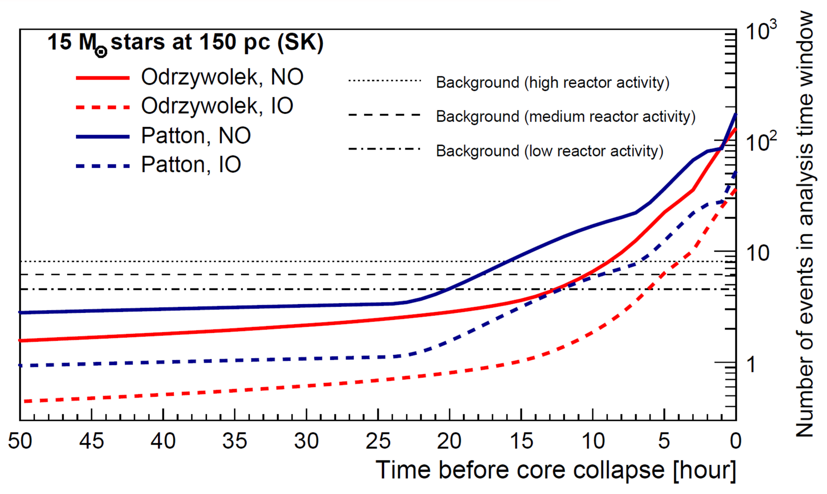
- ~2m pure water layer
- >1,800 8-inch PMTs facing outwards

SK-Gd [5]

- upgrade SK by dissolving Gadolinium to water
- Better neutron tagging capability
- **Pre-SN ν** potentially detectable!

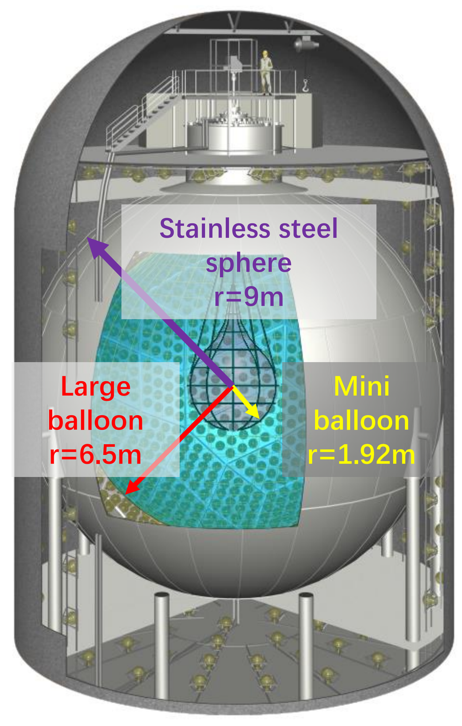
Advantage of SK-Gd: Lager target size

- Major background sources are **Reactor neutrinos**, geo-neutrinos, accidental coincidences and radioactive contaminations.
- Event selection based on Boosted Decision Tree method with multiple characteristic variables.



Number of pre-SN $\bar{\nu}_e$ events expected in SK in a running 12-hour time window.

3. Pre-SN Neutrinos in KamLAND



KamLAND [6]

- liquid scintillator detector in the Kamioka mine, same as SK

Inner detector

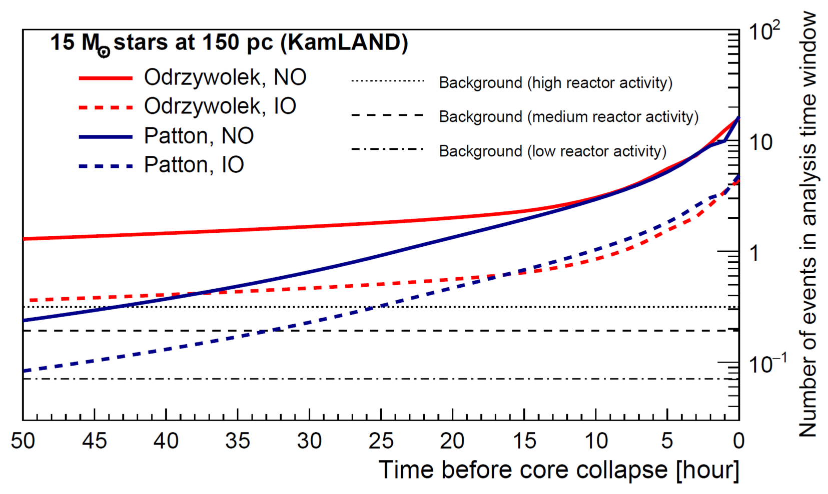
- Large balloon filled with 1-kton liquid scintillator (**this study**)
- Mini balloon filled with 745 kg Xe ($0\nu\beta\beta$)
- 1325 17-inch PMTs and 554 20-inch PTMs

Outer detector

- Cylinder tank filled with pure water
- 140 20-inch PMTs

Advantage of KamLAND: Low background rate

- Background sources include accidental coincidences, $\alpha - n$, geo-neutrinos and **Reactor neutrinos** (dominant)
- Energy and position based Likelihood event selection



Number of pre-SN $\bar{\nu}_e$ events expected in KamLAND in a running 24-hour time window.

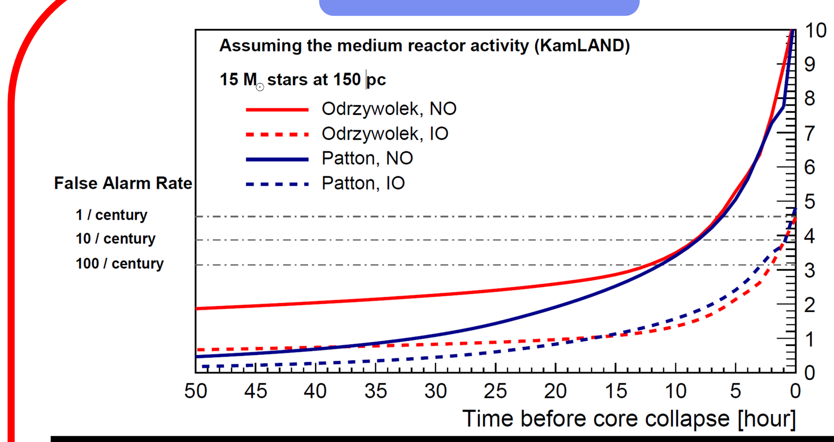
4. Combined alert

We construct a Likelihood ratio, where the Likelihood function is a product of the Poisson Likelihoods of SK and KamLAND. Each Poisson Likelihood is based on the event observed in the running analysis time window and the expected background rate. Background rates for SK and KamLAND are considered uncorrelated, as both experiments perform independent background measurements.

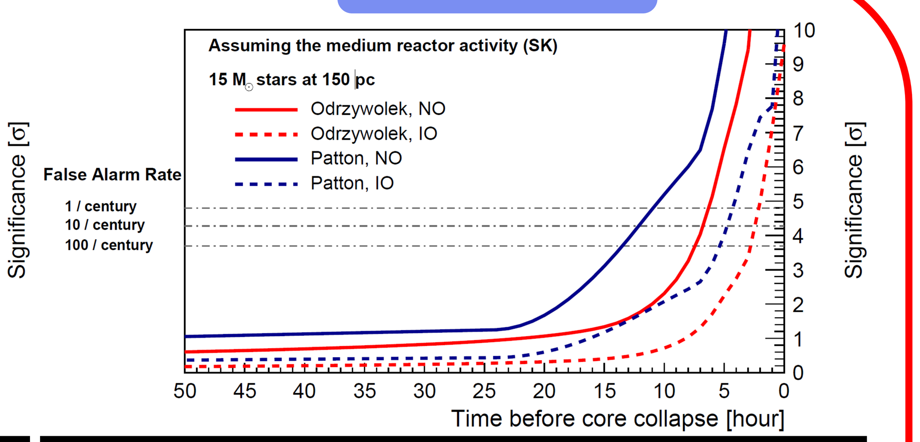
False alarm rate

- It could be misleading to simply convert the Likelihood ratio to p-value and consider it as false positive rate, because of the "**Look Else-where Effects**".
- To resolve the problem, we perform Monte-Carlo simulation to find out how frequently the system issues false alarms for any alarm threshold.
- The quantity "**false alarm rate**", which is the frequency of issuing false alarms in a century, is obtained.
- Ultimate alarm threshold is **false alarm rate ≤ 1/century.**

KamLAND



SK



Sensitivity of pre-SN $\bar{\nu}_e$ in KamLAND (left) and SK (right), as a function of time before core-collapse. The expected discovery significance are shown for 15 $M_\odot$ stars at 150 parsecs assuming Odrzywolek pre-SN model [1] and Patton pre-SN model [8], with normal and inverted neutrino mass orderings.
SK uses a 12-hour analysis window while KamLAND uses a longer 24-hour analysis window, both optimized for the two pre-SN models considered to obtain the longest warning time.

COMBINE

KamLAND

- Resolve a signal early thanks to low background.

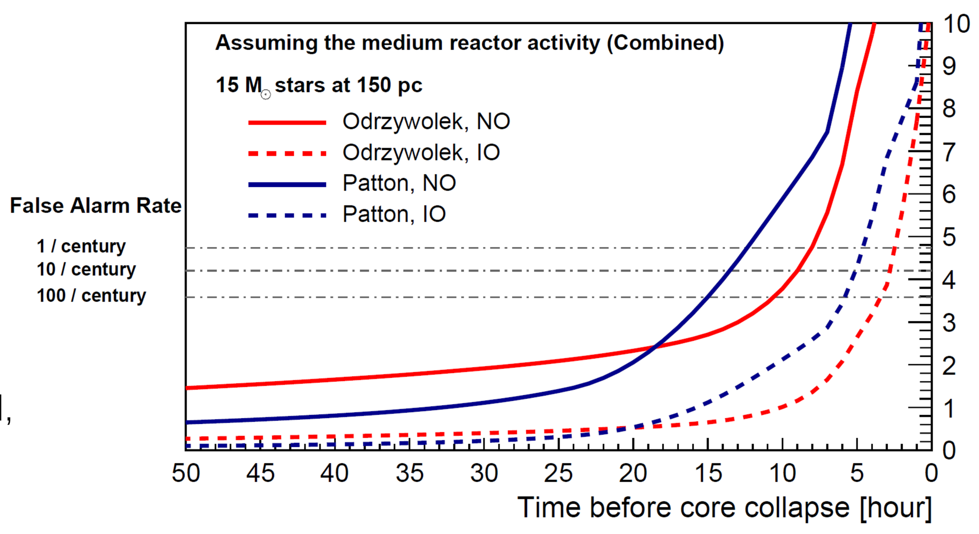
SK

- Large size help increasing significance.

Combined

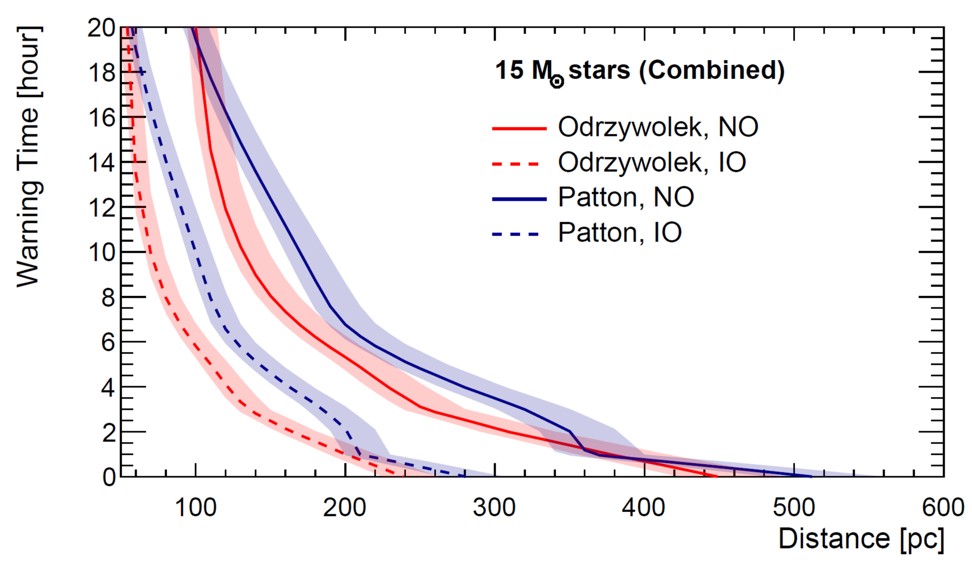
- Take advantages from both detectors

Can issue alert **at least 2 hours** before SN, assuming stars with 15 $M_\odot$ at 150 pc.



The sensitivity is also tested assuming different background conditions.

- Low reactor background: all reactors in Japan are turned off.
- Medium reactor background: close to the situation as of the winter of 2023-2024.
- High reactor background: roughly equivalent to all reactors in Japan are turned on.



Expected warning time as a function of distance of stars. The upper (lower) edge of the band is based on low (high) background level assumption.

At the medium background level, the best distance coverage of the combined alert for 15 $M_\odot$ progenitors is 510 pc.

With the highest background rate we considered, the combined alert remain sensitive to pre-SN neutrinos.

- Expected warning time of no less than 2.2 hours, assuming 15 $M_\odot$ at 150 pc.

Combined Pre-SN Alert Now ONLINE!

- Identical systems on both KamLAND server and SK server, which backup each other.
- False alarm rate simulation will run on SK side only, for it has more computing power.
- Provide pre-SN neutrino search results with the corresponding false alarm rate
- Update every 5 minutes
- Link to GCN via email-based circular
- Issues alert when a signal is found with false alarm rate ≤1/century

Registration open to the public: https://www.lowbg.org/presnalarm/
Registered users have access to the combined pre-SN neutrino search results.

5. Summary

A pre-supernova neutrino alert system combining the observations in KamLAND and Super-Kamiokande is online. It provides semi-realtime search results of pre-supernova neutrinos, and issues an alarm when a significant signal is observed with the corresponding false alarm rate no more than 1 per century.

Taking advantage of the complementary properties of these two detectors, the system is expected to issue an alert up to **12 hours before the CCSN of a 15 $M_\odot$ star at 150 pc**, longer than each of the individual detector does. Then distance coverage has also been extended to 510 pc, considering a 15 $M_\odot$ star and normal mass ordering.

References
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[2] K. Asakura et al. Astrophys.J. 818 (2016) 1, 91
[3] L.N. Machado et al. Astrophys.J. 935 (2022) 1, 40
[4] Y. Fukuda et al. Nucl.Instrum.Meth.A 501 (2003) 418-462
[5] J. F. Beacom, M. R. Vagins Phys.Rev.Lett. 93 (2004) 171101
[6] A. Gando et al. Phys.Rev.D 88 (2013) 3, 033001
[7] S.M. Adams et al. Astrophys.J. 778 (2013) 164
[8] K.M. Patton et al. Astrophys.J. 851 (2017) 1, 6