# Joint Pre-Supernova Monitor with Super-Kamiokande and KamLAND

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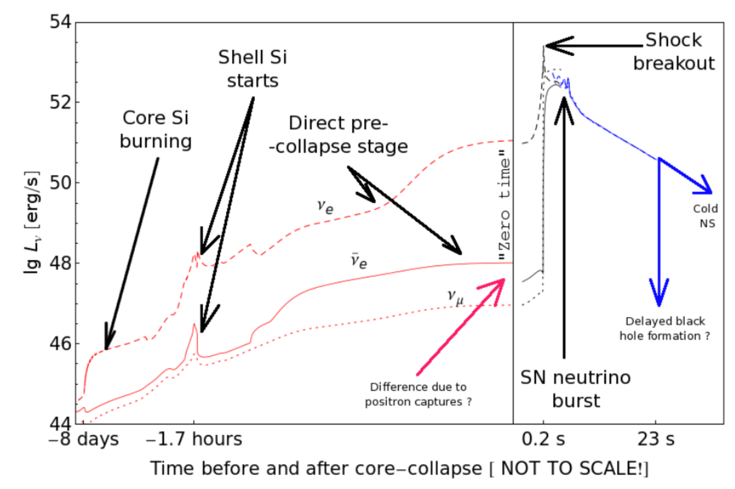
## Pre-Supernova Neutrinos




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**

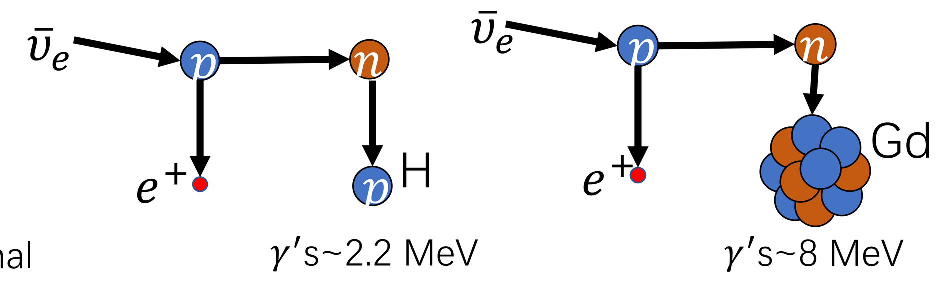
- Before core-collapse, the progenitor emits neutrinos of all flavors increasingly
- Starting at the silicon burning phase, a significant fraction of electron anti-neutrinos ($\bar{\nu}_e$) exceed inverse beta decay (IBD) threshold
- Potentially detectable, thus can be early warnings of a SN

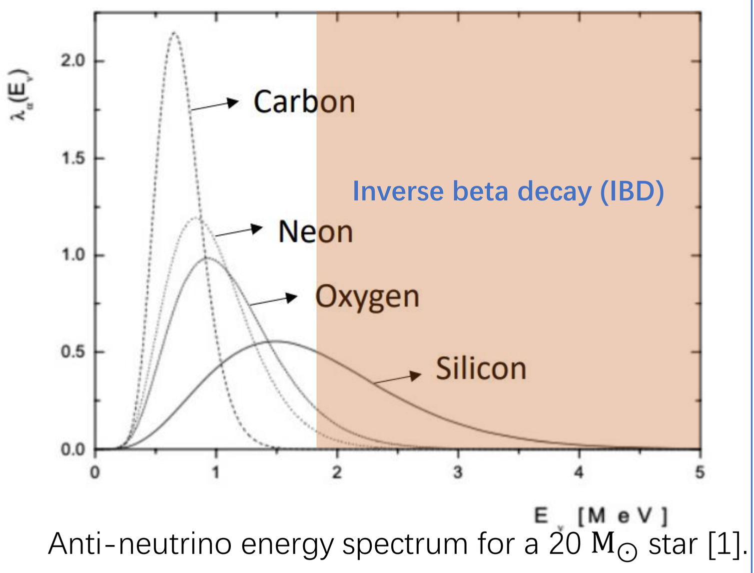
**Pre-SN monitors**

- KamLAND pre-SN monitor online in 2015 [2]
- Super-K also set a pre-SN monitor in 2021 [3]

**Joint pre-SN monitor with Super-K and KamLAND**

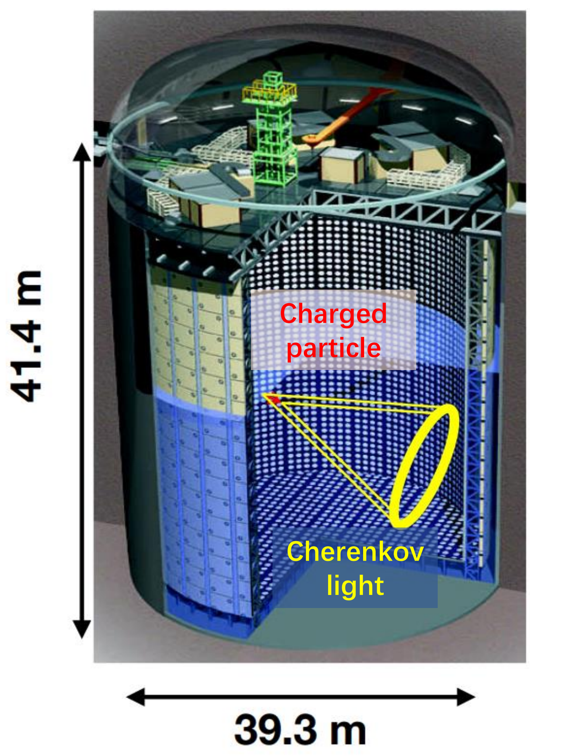
- Developed to improve sensitivity to pre-SN neutrino signal




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

## Pre-SN Neutrinos in Super-K




**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**

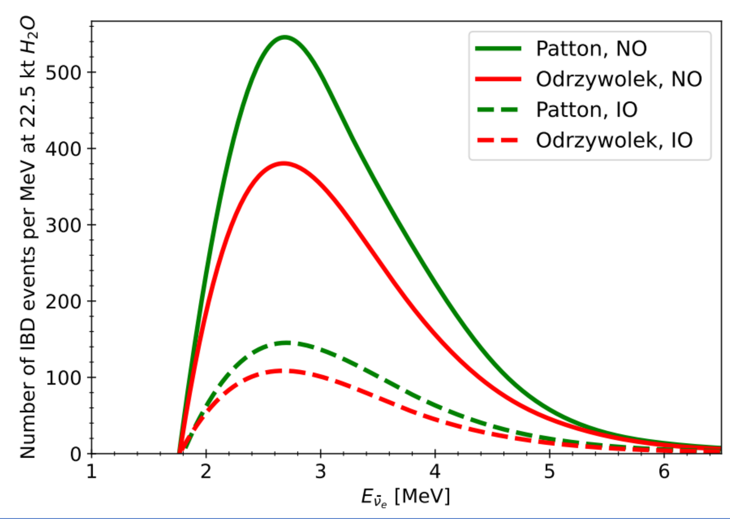
- ~2m pure water layer
- >1,800 8-inch PMTs facing outwards

**SK-Gd** [5]

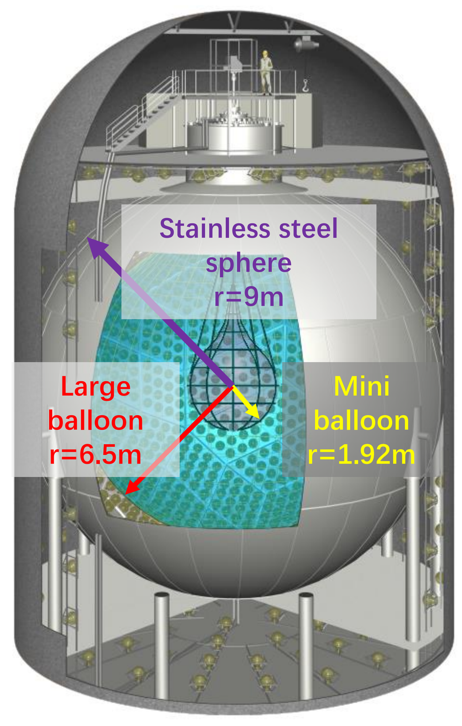
- upgrade Super-K by dissolving Gadolinium to water
- Better neutron tagging capability
- **Pre-supernova $\nu$** potentially detectable!

Advantage of SK-Gd: Lager target size

- Number of pre-supernova $\bar{\nu}_e$ events detected in the 22.5 kt Super-K fiducial volume over the last 10 hours prior to the core-collapse as a function of the neutrino energy, assuming stars with 15 $M_\odot$ at 150 pc [3].
- 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.




## Pre-SN Neutrinos in KamLAND




**KamLAND** [6]

- liquid scintillator detector located in the Kamioka mine

**Inner detector**

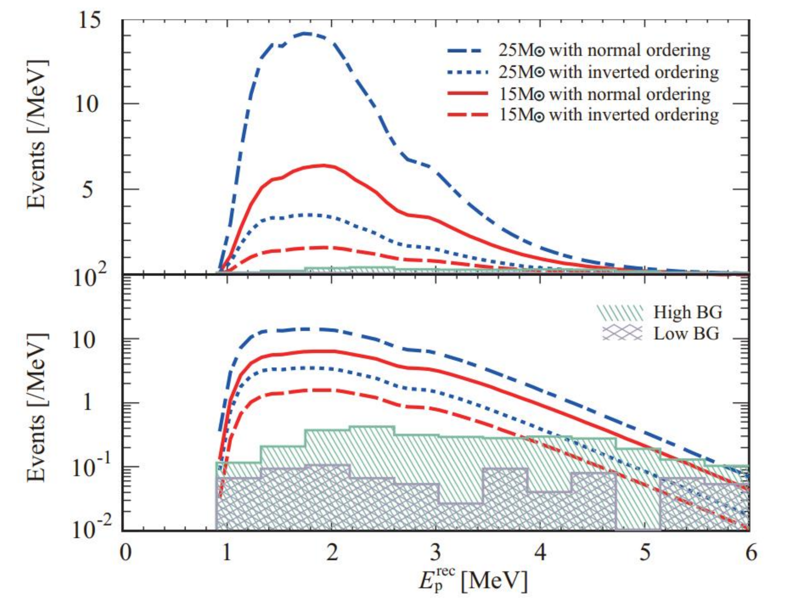
- Large balloon filled with 1-kton liquid scintillator (**this study**)
- Mini balloon filled with 745 kg Xe ($0\nu\beta\beta$)
- 1325 17-inch PMTs and 554 20-inch PTMs

**Outer detector**

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

Advantages of KamLAND:
- Low energy threshold: $E_{th} \geq 1.8$ MeV
- Low background rate

- The integrated pre-SN neutrino energy spectrum over the last 48 hours before core-collapse [2]
  - Considering Odrzywolek pre-SN model
  - Assuming stars at 200 pc
- Background sources include accidental coincidences, $\alpha - n$, geo-neutrinos and **Reactor neutrinos** (dominant)
- Energy and position based Likelihood event selection




## Methodology

Super-K and KamLAND are Poisson counting experiments. Without explicit reference to a pre-SN model, we perform a **test of significance.**

The joint search uses a Likelihood function, which is a product of the Poisson Likelihoods of Super-K and KamLAND:

$$\mathcal{L} = Poisson(n_{SK}^{obs}|S_{SK} + B_{SK}) \times Poisson(n_{KL}^{obs}|S_{KL} + B_{KL})$$

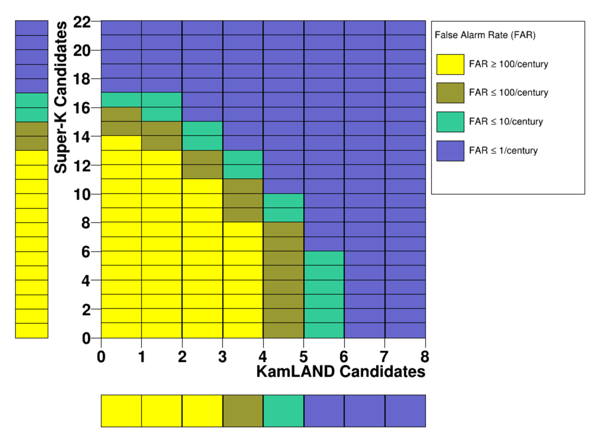
where the subscript "SK" represents Super-K, "KL" represents KamLAND. $n^{obs}$ are observed numbers of candidates, $S$ are parameters representing signal contributions and $B$ are parameters representing background contributions.

**Correlations are not considered**.

- Reactor/Geo neutrino background are correlated in nature.
- Both experiments utilize data over a past period (weeks or months) as background measurement.
- We neglect background uncertainties, and consider no correlations between the background rates.

**False alarm rate**

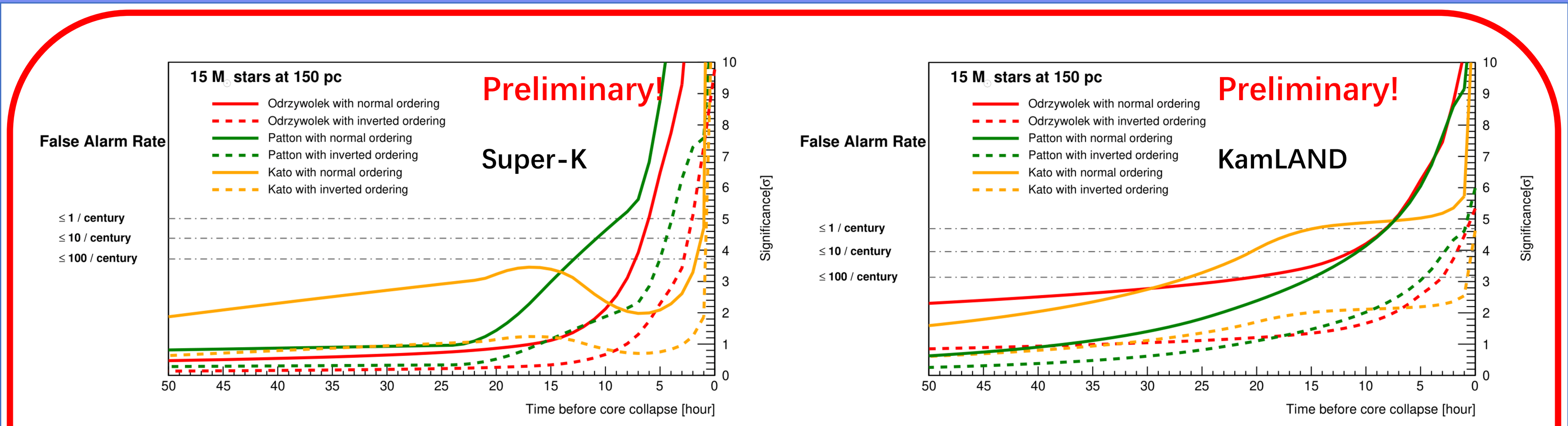
- We found **difficulties in reporting the results**. For example, setting the significance level to $3\sigma$ does not mean the false positive rate is 0.3%.
- The semi-realtime search update every few minutes, each utilizing data over a few hours. Therefore, there is an overlap between a measurement and the next one, making them **not fully independent**. In addition, the "**Look Else-where Effects**" also cause difficulty in reporting the results.
- To resolve the problem, we use the quantity "**false alarm rate**", which is the frequency of getting false positives in a century, extracted from toy Monte-Carlo assuming background-only scenario.




An example of resultant false alarm rate from toy Monte-Carlo simulation. The rate of galactic core-collapse supernova explosions is taken to be $3.2^{+7.3}_{-2.6}$ per century [7]. Considering this factor, we set the alarm threshold to **False Alarm Rate $\leq$ 1/century**.

- Once the observation drops in the blue regions, we claim a significant pre-SN neutrino signal.

## Sensitivity Study




Sensitivity of pre-SN $\bar{\nu}_e$ in Super-K (left) and KamLAND (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], Patton pre-SN model [8] and Kato pre-SN model [9], with normal and inverted neutrino mass orderings.
Super-K uses an 8-hour analysis window while KamLAND uses a longer 24-hour analysis window, both optimized for the three pre-SN models considered to obtain the longest warning time.

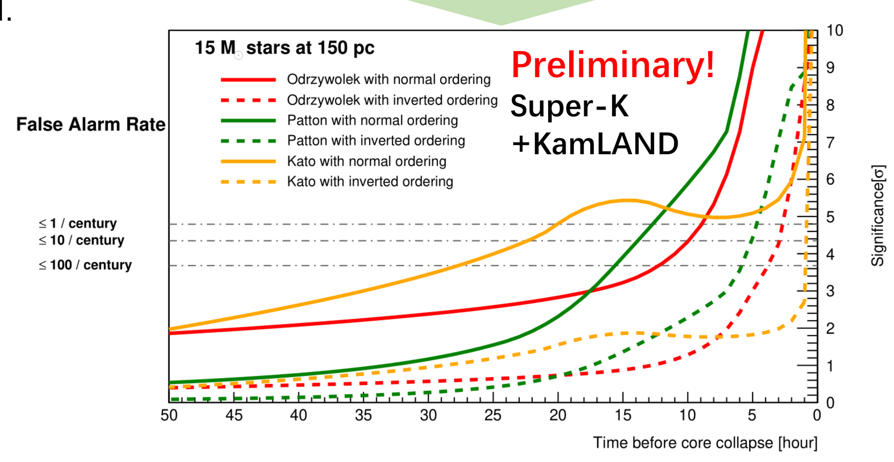
combined

**KamLAND**
- Resolve a signal early thanks to low background.

**Super-K**
- Large size help increasing significance.

**Combined**
- Take advantages from both detectors

Assuming stars with 15 $M_\odot$ at 150 pc, we can claim a significant pre-SN signal with false alarm $\leq$ 1/century at least 9 hours (1 hour) before SN, for all models with normal (inverted) ordering.



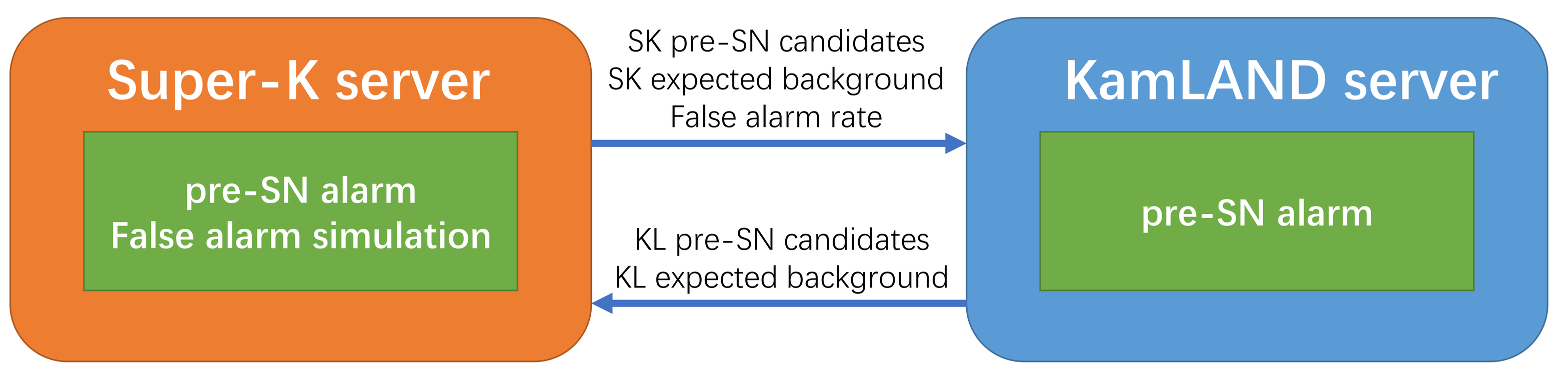

## Alert System

A joint pre-SN alert system is developed

- Now test running on both Super-K side and KamLAND side
- The alert system itself will run on both sides
- False alarm rate simulation will run on Super-K side only, for it has more computing power.

**Functions**

- Provide combined significance of pre-supernova neutrinos with the corresponding false alarm rate
- Update every 5 minutes
- Link to GCN (may begin with an email-based GCN circular)




*Will be online soon. Stay tuned!*

**References**

[1] A. Odrzywolek et al. Acta.Phys.Pol.B, 41 (2010) 1611-1628
[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
[9] C. Kato et al. Astrophys.J. 848 (2017) 1, 48