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# Combined Super-Kamiokande and KamLAND pre-supernova alarm


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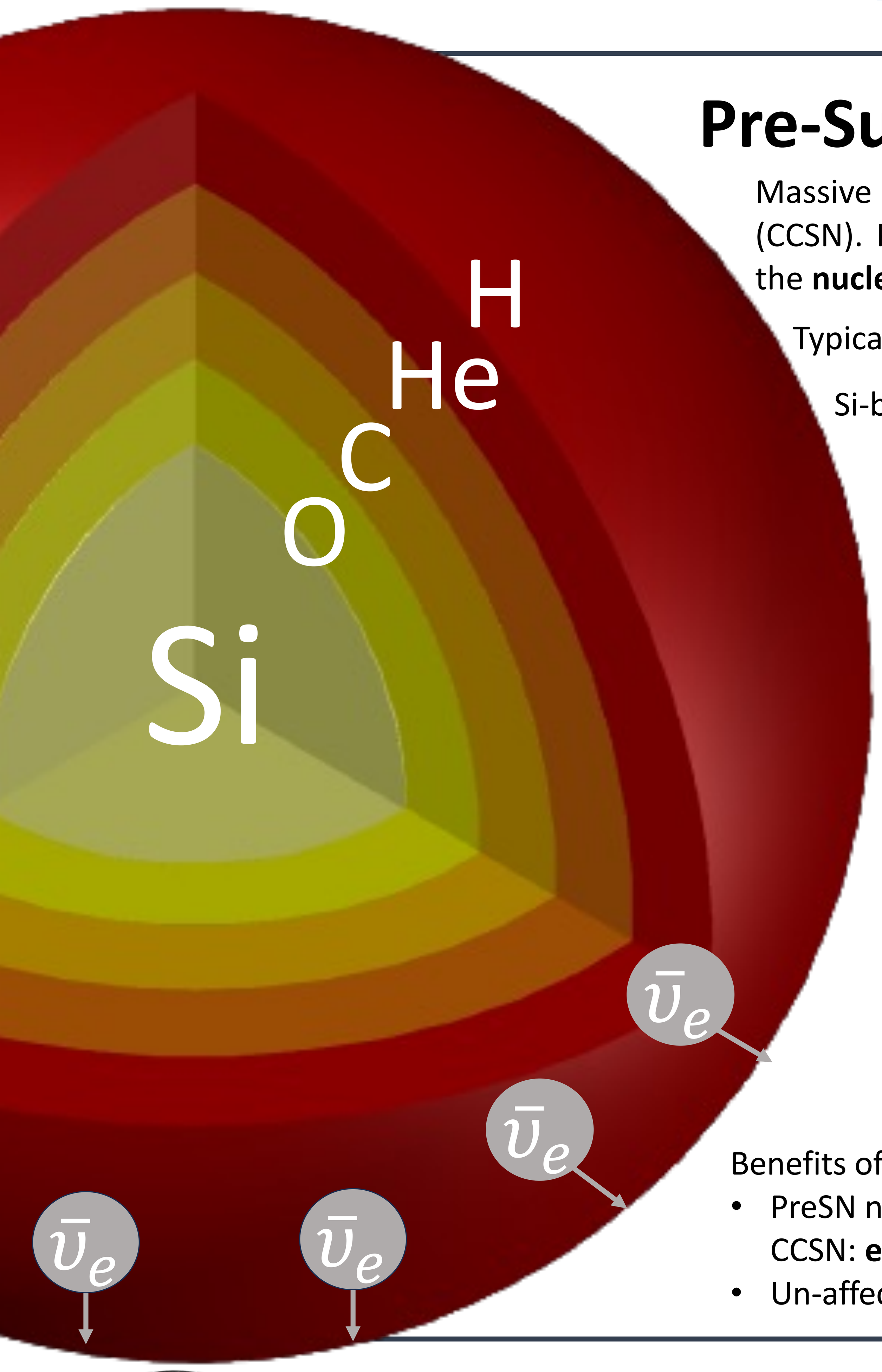
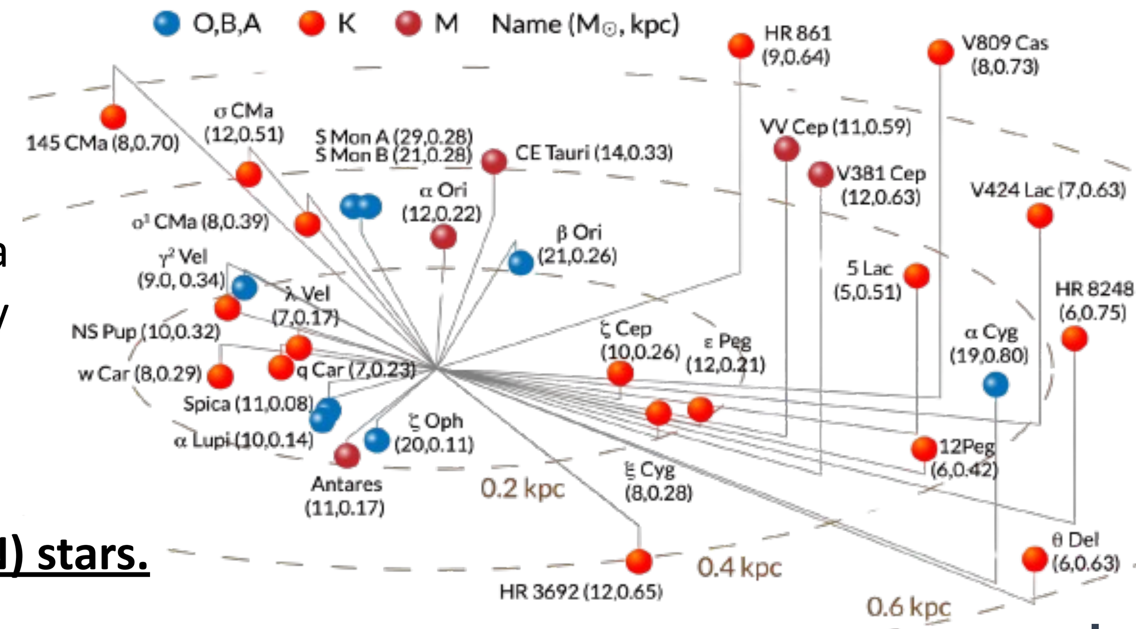



## Pre-Supernova Star

Massive stars (M > 8M$_\odot$) may end their lives in a core collapse supernova (CCSN). Prior to the collapse of their cores, these stars are supported by the **nuclear fusion** of heavy nuclei in their cores:

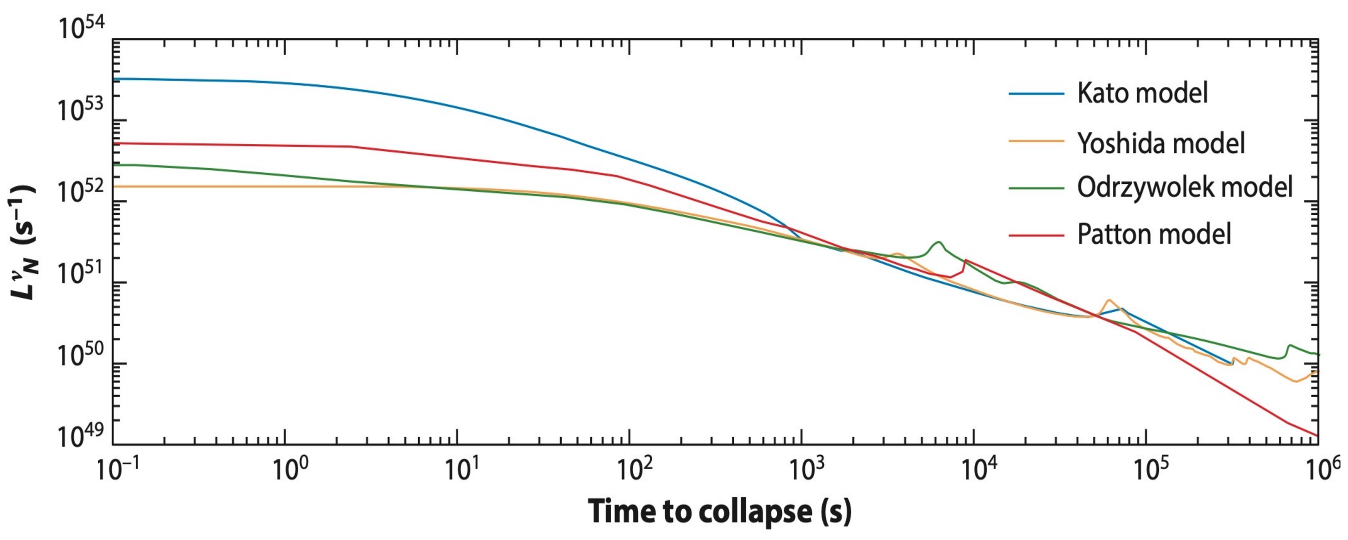
Typically, helium (He), carbon (C), oxygen (O), neon (Ne) and silicon (Si).

Si-burning stage: stars are commonly known as **pre-supernova (preSN) stars.**

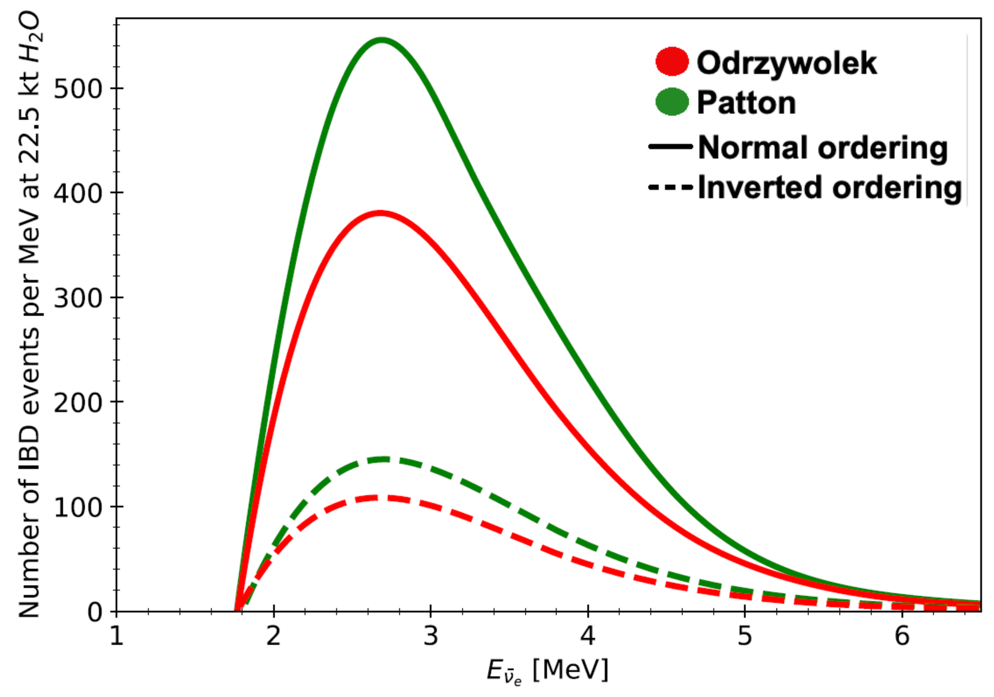



*Pre-supernova star candidates. Edited from [1].*

Main cooling mechanism → Neutrino emission (thermal and nuclear processes) → PreSN $\bar{\nu}_e$ can be detected in Super-Kamiokande and KamLAND




*Neutrino luminosity for different preSN models [2].*

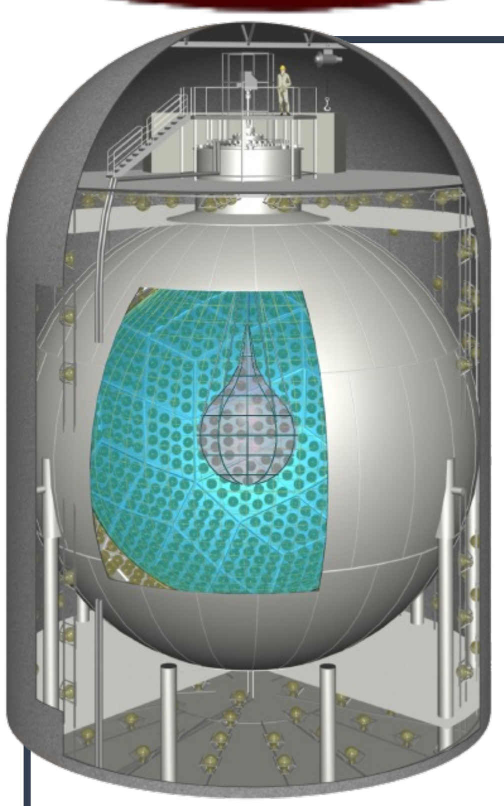



*Expected IBD events in Super-Kamiokande for preSN models [3] and [4]. From [5]. For normal (solid line) and inverted (dashed line) neutrino mass ordering.*

Benefits of a preSN neutrino detection:

- PreSN neutrinos are emitted over a very long timescale before CCSN: **early warning system for supernovae.**
- Un-affected observation of the interior of stars;
- Understand physical processes leading to CCSN;
- Evidence for neutrino mass ordering;
- Confirm the existence of shell burning.

## KamLAND-Zen



KamLAND-Zen: 1 kton liquid scintillator detector. In operation since 2002.

- Inner detector: 1,325 17-inch + 554 20-inch PhotoMultiplier Tubes (PMTs).
- Outer detector: water Cherenkov – 140 20-inch PMTs.

Ultra low background detector. KamLAND can detect low-energy $\bar{\nu}_e$ through IBD:

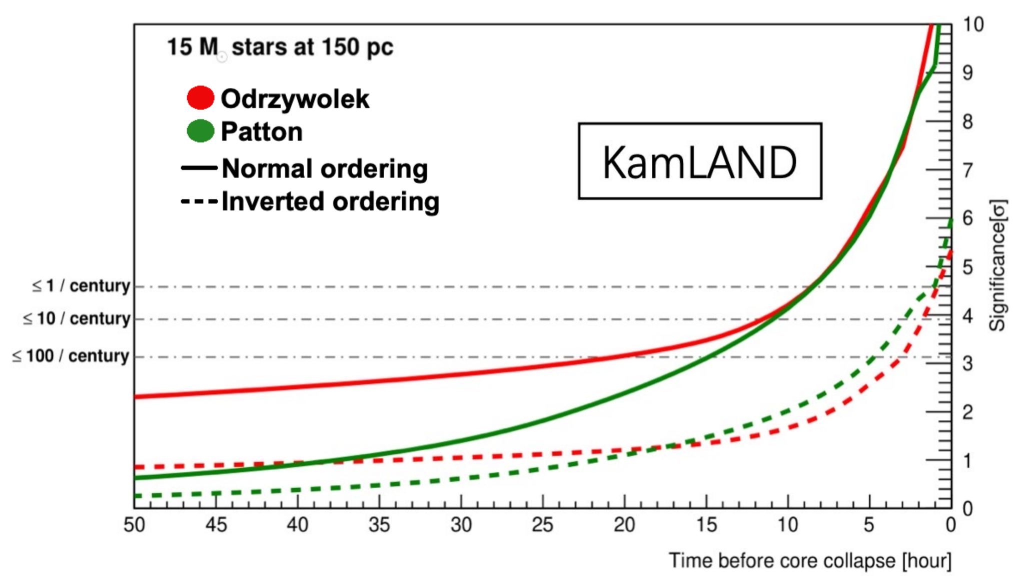
- $e^+$: scintillation light from $e^+$ + 2 γ-rays (pair annihilation).
- $n$: 2.2 MeV γ -ray through neutron capture on H.

Very low background + high sensitivity to $\bar{\nu}_e$: **pre-supernova neutrinos**.

Main background sources [6]:

- Geoneutrinos;
- Reactor neutrinos;
- (α,n) interactions;
- Accidental coincidences.

Event Selection: time/spatial correlation between IBD products and energy cuts.

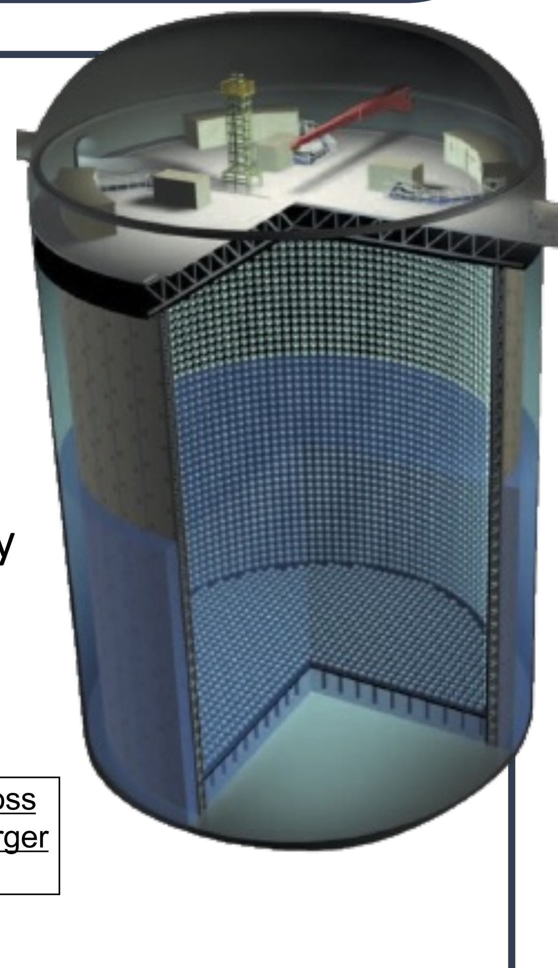



*Evolution of detection significance in KamLAND as a massive star (d = 150 pc) approaches the core collapse.*

## Super-Kamiokande

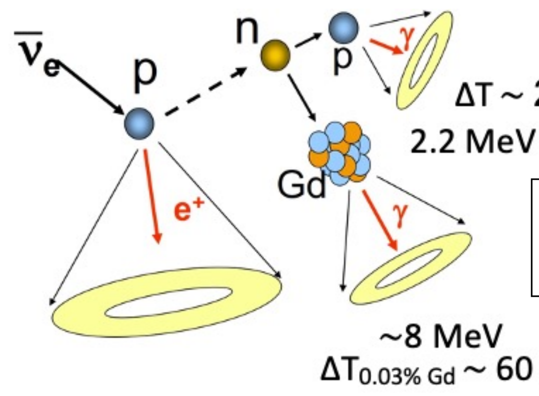
Super-Kamiokande (Super-K): 50 kton water Cherenkov detector. In operation since April 1996.

- Inner detector: ~11,000 20-inch PMTs.
- Outer detector: ~2,000 20-inch PMTs.



In 2020 (SK-Gd) → loaded **$Gd_2(SO_4)_3$ * $8H_2O$**: improve sensitivity to low energy $\bar{\nu}_e$ [7].

0.03% Gd: ~75% captures on Gd.



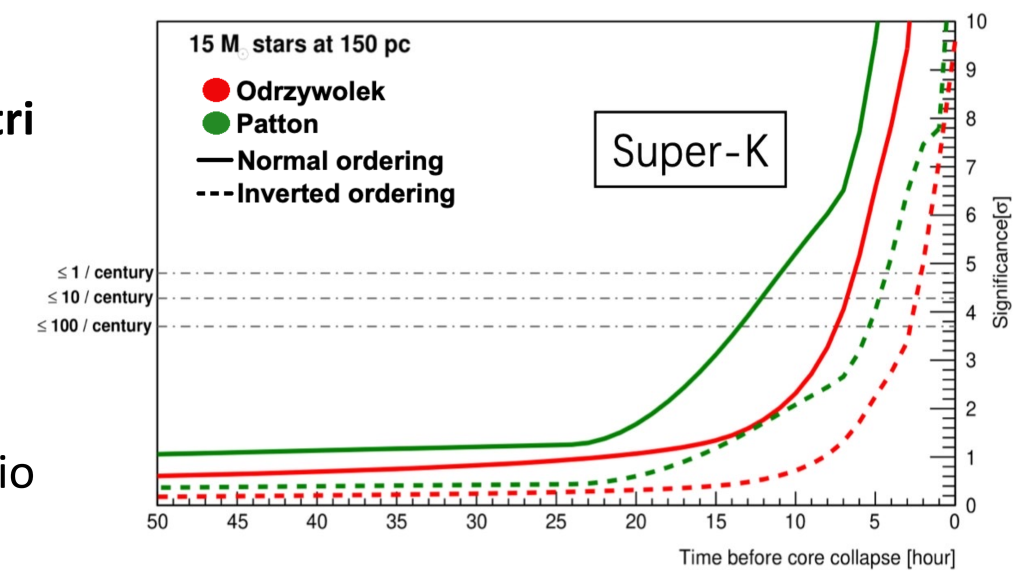

Neutron capture cross section 100,000x larger in Gd than H.

SK-Gd: Diffuse Supernova Neutrino Background and **pre-supernova neutri**

Main background sources [5]:

- Accidental coincidences;
- Reactor neutrinos.

Event Selection: time/spatial correlatio between IBD products and Boosted Decision Tree.




*Evolution of detection significance in Super-Kamiokande with 0.03% Gd as a massive star (d = 150 pc) approaches the core collapse.*

## Combined Alarm

KamLAND preSN alarm has been in operation since 2015 [6] and in Super-K since 2021 [5].

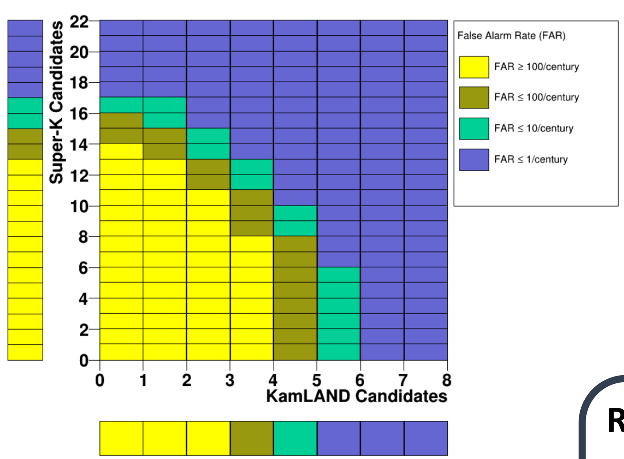
Both alarms perform test statistics with the number of events found in real-time inside a time window and expected background → Poisson counting.

Agreement established between Super-Kamiokande and KamLAND to combine both pre-supernova alarms:

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

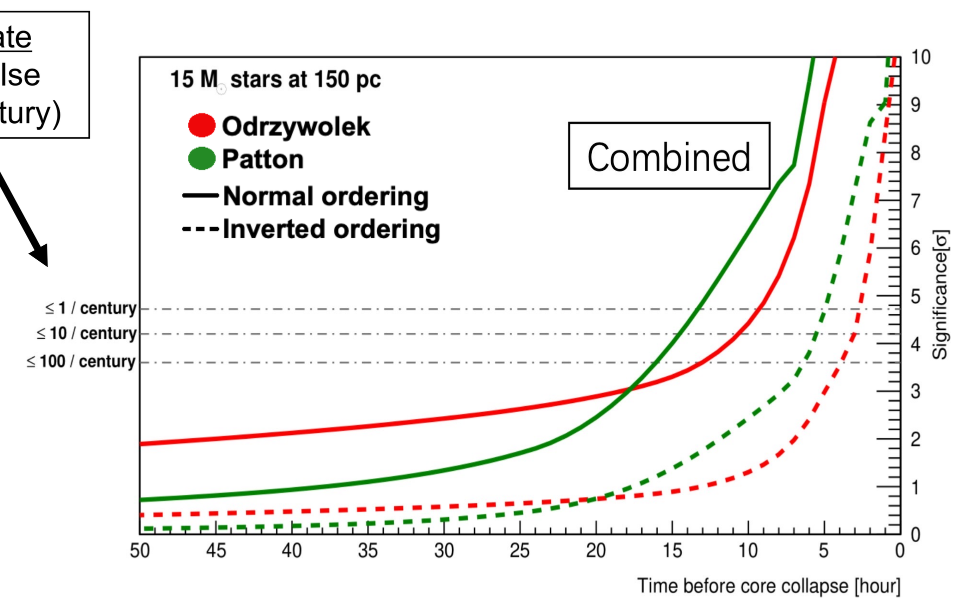
$n^{obs}$: number of candidate
$S$ : Expected signal number
$B$ : Expected background number

Assumes no correlations between backgrounds

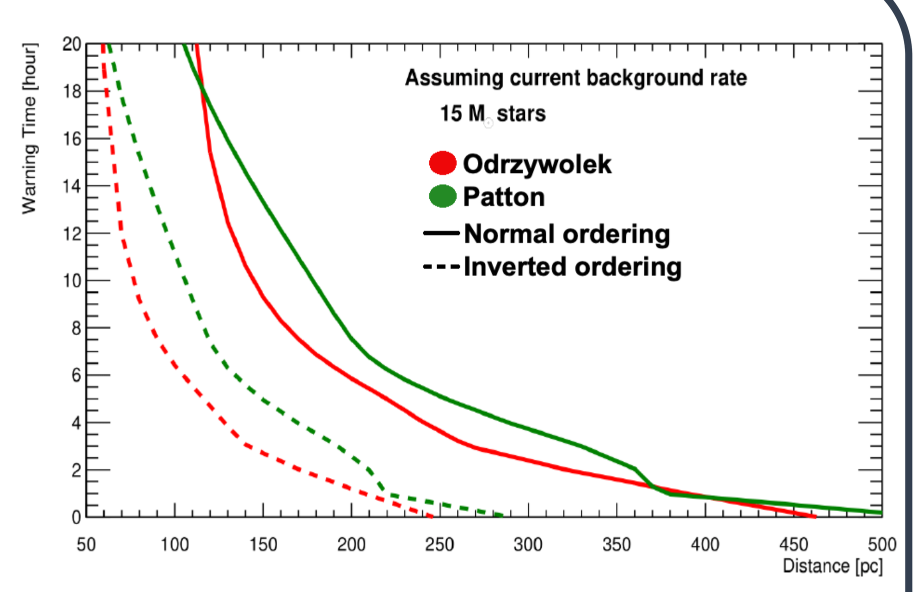



KamLAND low background + Super-K large volume = Extended warnings and detection range

False Alarm Rate (frequency of false positives per century)




*Evolution of detection significance of combined alarm as a massive star (d = 150 pc) approaches the core collapse.*




*Warning hours of combined alarm in function of preSN star distance (false alarm rate < 1/century)*

The combined alarm was launched in May 2023, and it is open to public: https://www.lowbg.org/presnalarm/

If number of false positives is less than one per century: GCN circular


**References:** **[1]** *Mukhopadhyay, et al, 2020 ApJ 899 153,* **[2]** *Ann.Rev.Nucl.Part.Sci. 70 (2020) 121-145,* **[3]** Odrzywolek, et al 2010 Acta Phys. Pol., **[4]** B 41, 1611 and Patton, et al 2017 ApJ 851 6, **[5]** L. N. Machado et al 2022 ApJ 935 40, **[6]** *K. Asakura et al Astrophys.J.* 818 (2016) 1, 91, **[7]** Beacom, Vagins PRL.93, (2004) 171101.