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#75

Combined KamLAND and Super-Kamiokande Pre-Supernova Alarm

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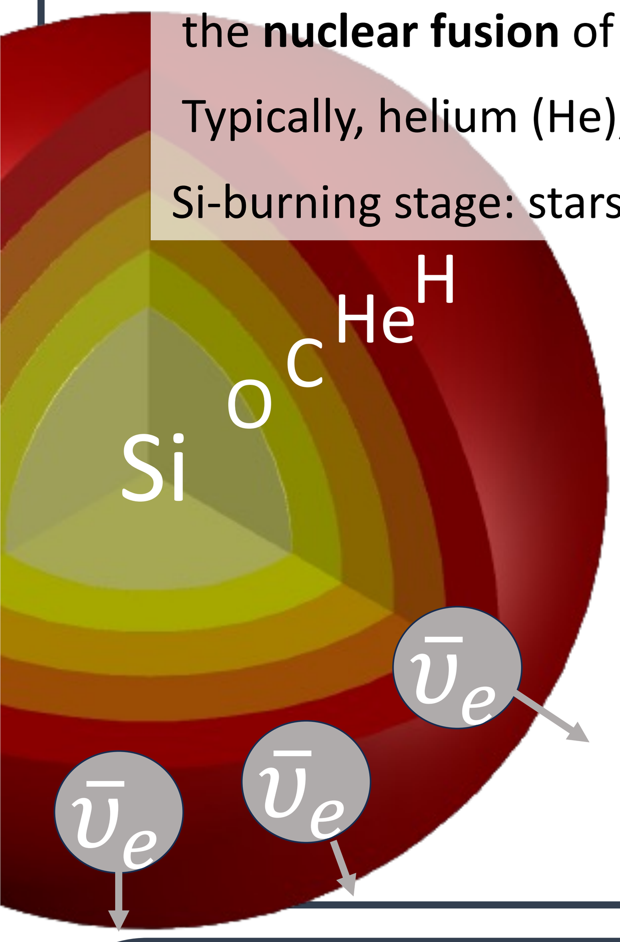
Pre-Supernova Star

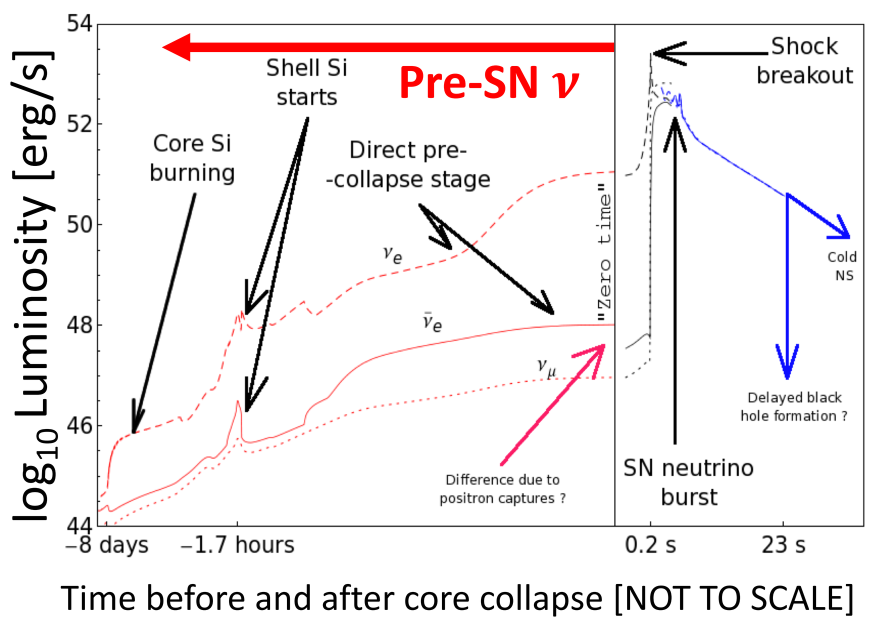
Massive stars ($M > 8M_{\odot}$) may end their lives in a core collapse supernova (CCSN). Prior to the collapse of their cores, these stars are supported by the **nuclear fusion** of heavy nuclei in their cores:

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

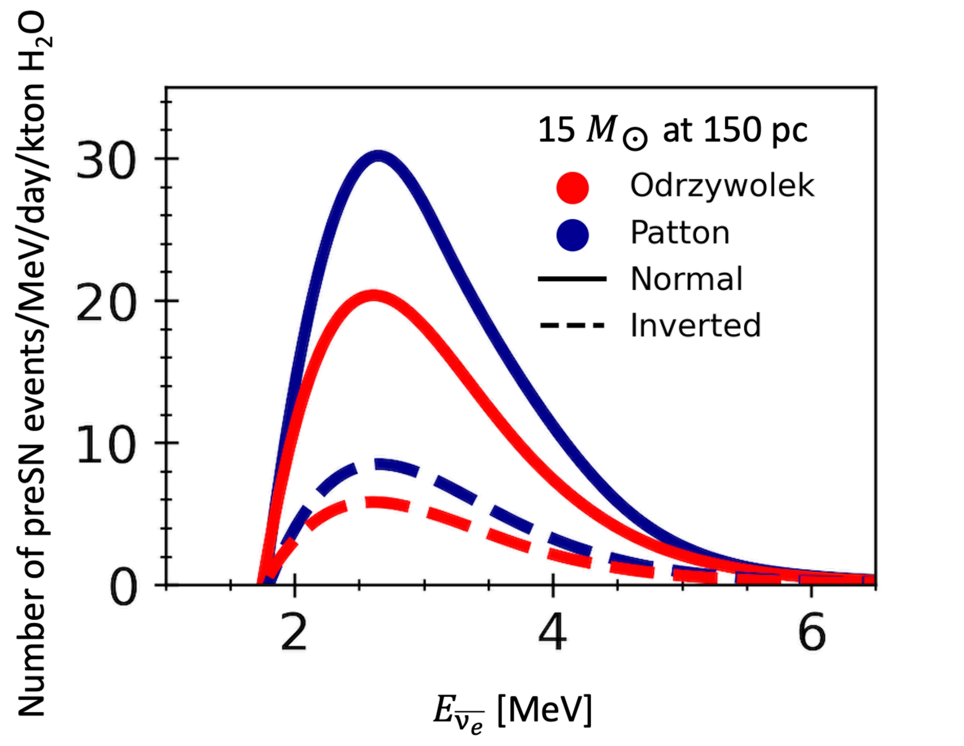
Si-burning stage: stars are commonly known as **pre-supernova (preSN) stars.**



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



Evolution of Pre-SN neutrino and SN neutrino luminosity [1]

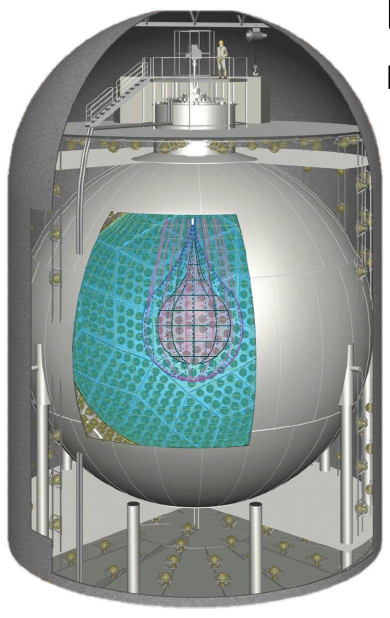


Expected IBD events in Super-Kamiokande for preSN models [2] and [3]. From [4]. For normal (solid line) and inverted (dashed line) neutrino mass ordering.

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

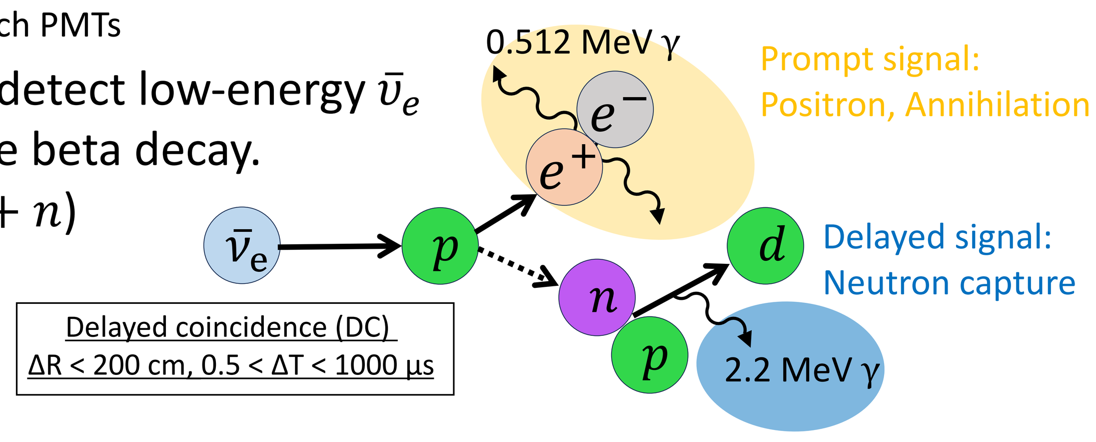
Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND)



KamLAND: 1 kton liquid scintillator (LS) detector located in Kamioka mine in Japan (1000m depth). In operation since March 2002.

- Inner detector: liquid scintillator main detector (r=6.5 m)
  (80% Dodecan, 20% Psedocumene and 1.36 g/L PPO)
  – 1,325 17-inch + 554 20-inch PhotoMultiplier Tubes (PMTs)
- Inner balloon with Xe loaded LS for 0νββ search (Volume cut, r=1.92 m)[5]
- Outer detector: muon veto water Cherenkov detector
  – 140 20-inch PMTs

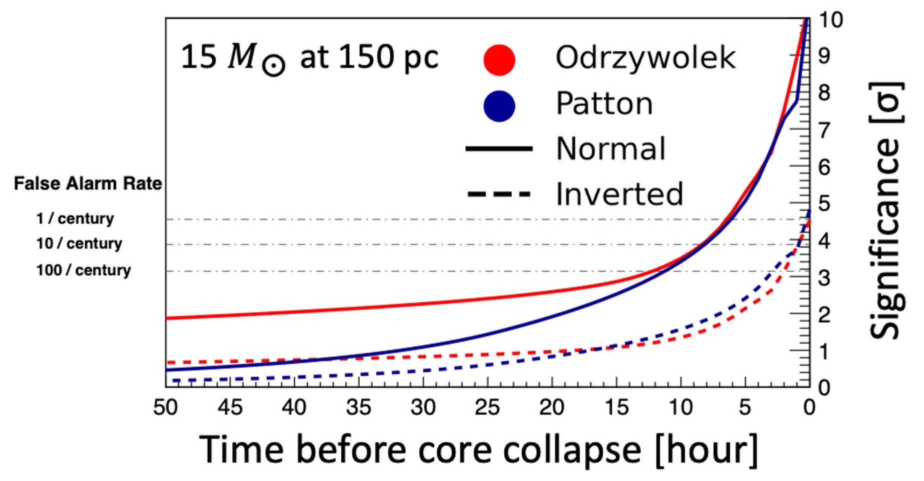
KamLAND can detect low-energy $\bar{\nu}_e$ through Inverse beta decay.
$(\bar{\nu}_e + p \rightarrow e^+ + n)$



Event Selection: time/spatial correlation between Inverse beta decay products and energy cuts.

Main background sources [6]:

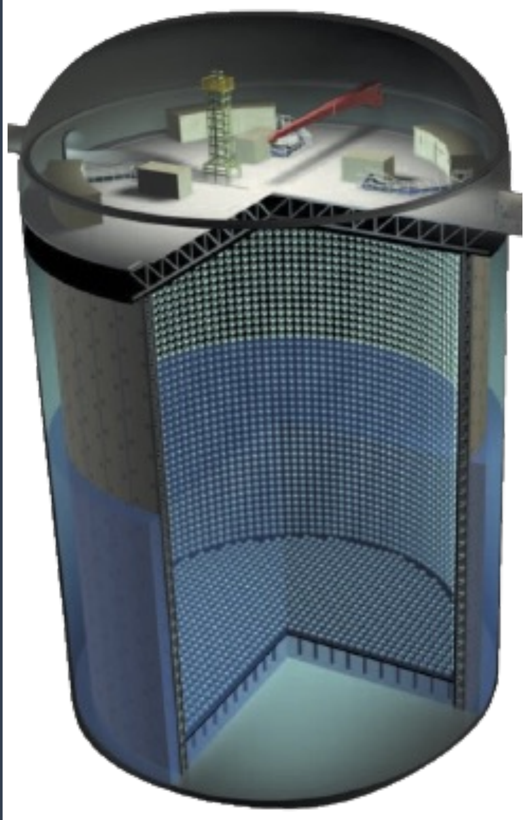
- Geoneutrinos
- Reactor neutrinos
- (α,n) interactions
- Accidental coincidences



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

Low background rate (0.19 /day) helps to issue earlier warning.

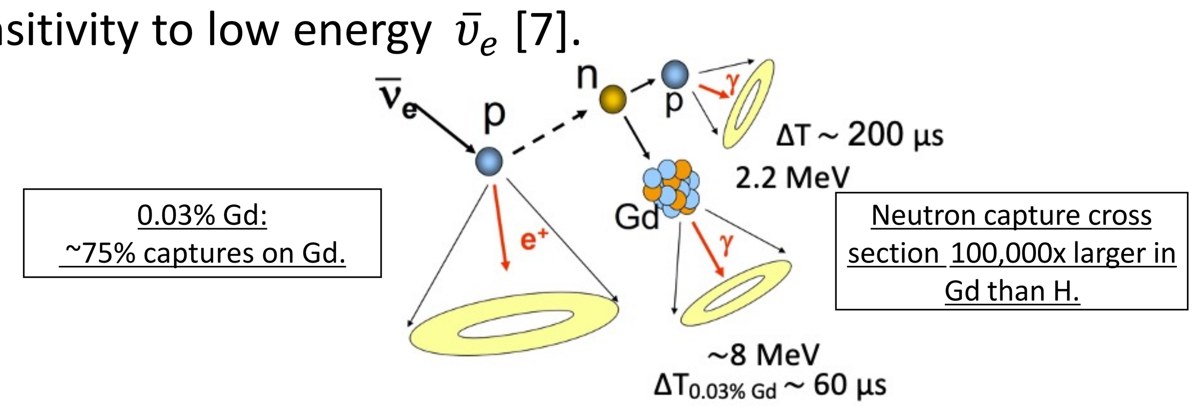
Super-Kamiokande (Super-K)



Super-K: 22.5 kton water Cherenkov detector located in Kamioka mine in Japan. In operation since April 1996.

- Inner detector: main detector
  (Cylinder volume, R=16.9m,h=36.2m)
  – ~11,000 20-inch PMTs
- Outer detector: muon veto detector (~2m pure water layer)
  – 1,885 20-inch PMTs

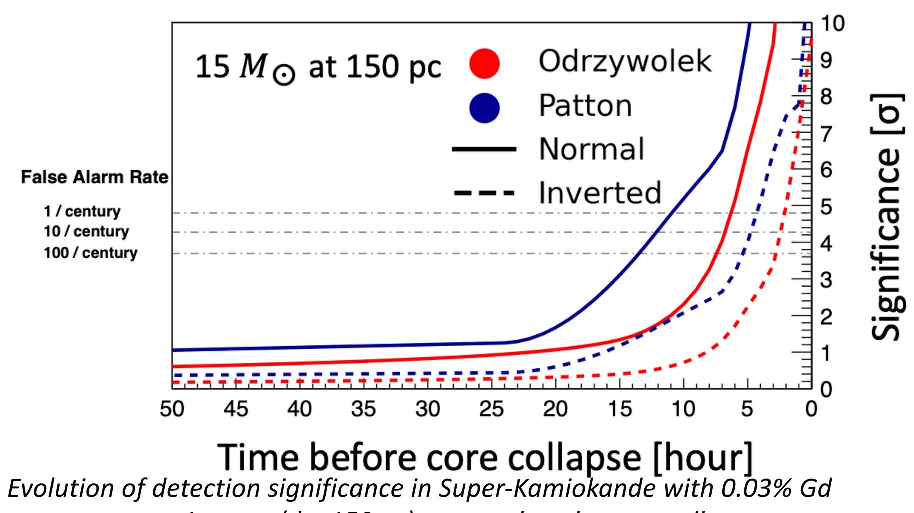
In 2020 (SK-Gd) → loaded $\mathbf{Gd_2(SO_4)_3 * 8H_2O}$: improve sensitivity to low energy $\bar{\nu}_e$ [7].



Event Selection: time/spatial correlation between Inverse beta decay products and Boosted Decision Tree.

Main background sources [4]:

- Accidental coincidences
- Reactor neutrinos



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

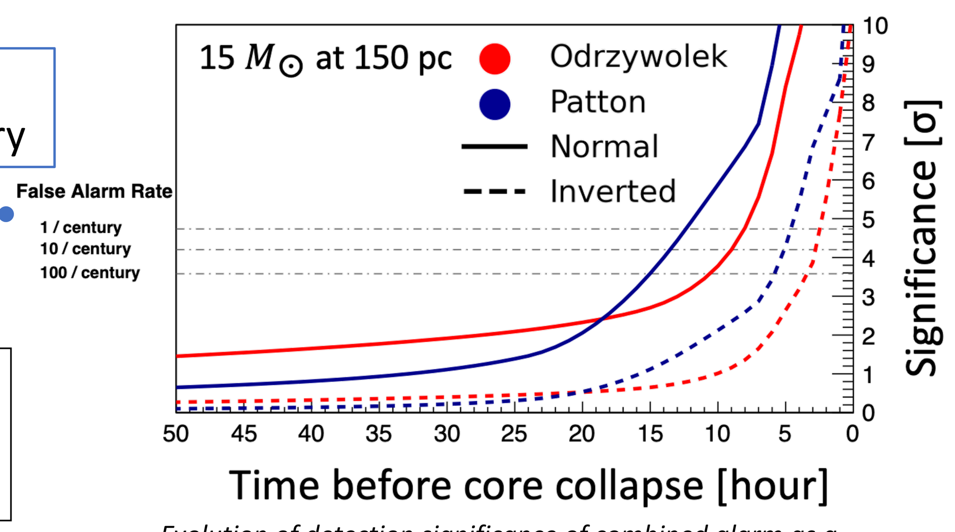
Large fiducial volume (22.5kton) leads to a rapid increase of significance.

Combined Alarm

KamLAND preSN alarm has been in operation since 2015 [6] and in Super-K since 2021 [4].
Agreement established between Super-K and KamLAND to combine both pre-supernova alarms.

KamLAND, Super-K and combined alarm all provide significances based on the statistical excess above the background rate.

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.

KamLAND Earlier warning + **Super-K** Rapid increase of significance
↓
Combined Take both advantages

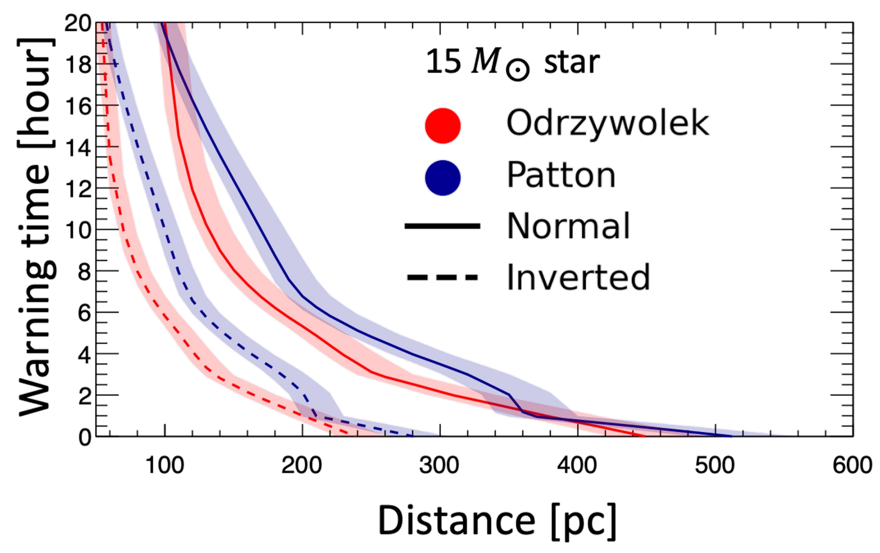
Warning time [hour]
(Expected significance corresponding to False Alarm Rate < 1/century)

Model	Mass ordering	KamLAND	Super-K	Combined
Odrzywolek	Normal	6.5	6.3	**8.0**
	Inverted	N/A	2.1	**2.5**
Patton	Normal	6.1	10.9	**12.4**
	Inverted	0.2	4.3	**4.6**

Combined alarm provides earlier warning than individual alarms.

This plot considers three possible future operation scenario for Japanese reactors.

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



Expected warning time of combined alarm as a function of distance. The lines are estimations assuming medium reactor activity. The upper (lower) edges of the bands are for the low (high) reactor activity.

Assuming normal ordering, Patton model and medium reactor activity,
the combined alarm can cover 15 solar mass stars within 510 parsecs.

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

- Running in both KamLAND and Super-K side (redundancy system)
- Expected Background: averaged event number over a past period (KamLAND 90days, Super-K: 30days)
- Total latency time ~ 6 min
- Output every 5 minutes
- Link to GCN via email-based circular

References: **[1]** *Ann.Rev.Nucl.Part.Sci. 70 (2020) 121-145*, **[2]** Odrzywolek, et al 2010 Acta Phys. Pol., **[3]** B 41, 1611 and Patton, et al 2017 ApJ 851 6, **[4]** L. N. Machado et al 2022 ApJ 935 40, **[5]** S. Abe *et al* Phys. Rev. Lett. **130**, 051801 **[6]***K. Asakura et al Astrophys.J.* 818 (2016) 1, 91, **[7]** Beacom, Vagins PRL.93, (2004) 171101.