TAUP VIENNA 2023

XVIII International Conference on Topics in Astroparticle and Underground Physics 2023

Super-Kamiokande Pre-Supernova Alarm and Combined Monitoring with KamLAND

August 31st, 2023

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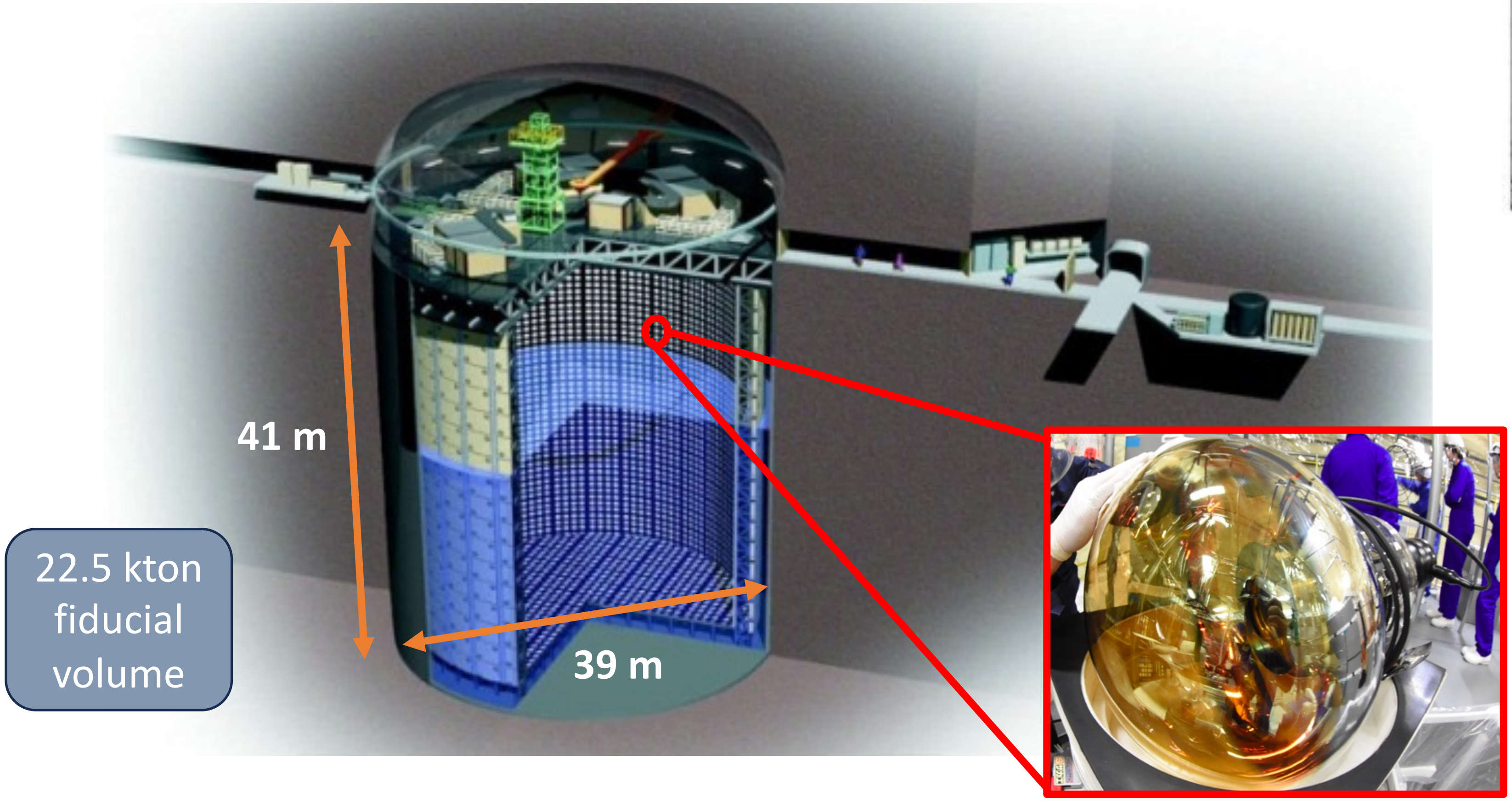
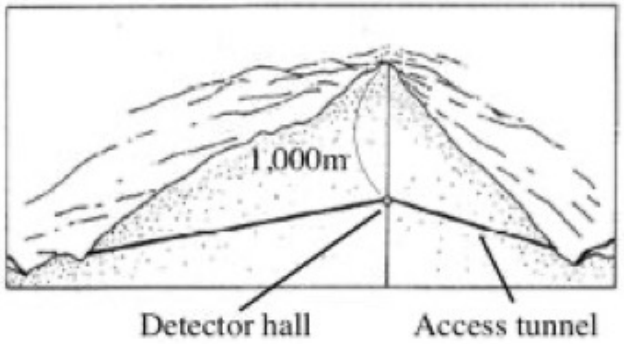
University of Glasgow

The Super-Kamiokande Experiment

The Super-Kamiokande (SK) Neutrino Detector is a 50 kton water Cherenkov located in the Kamioka mine in Japan, overburden with 1000 m of rock. In operation since April 1996.





Inner detector: currently has around 11,000 20-inch PhotoMultipliers Tubes (PMTs).

Outer detector: water layer ~2m thick, with ~1,885 8-inch PMTs, facing the outside of the detector.

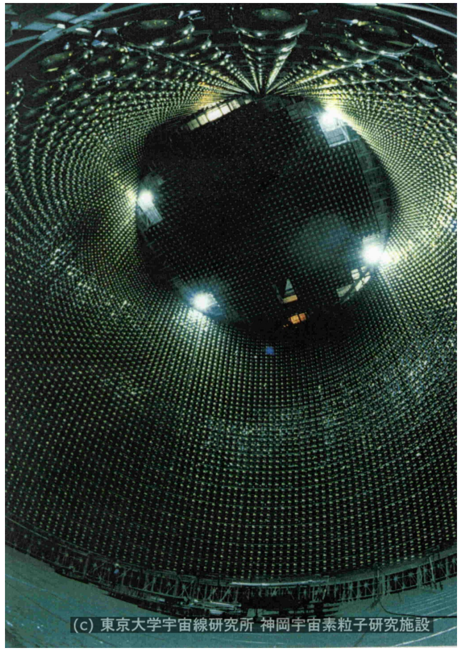
The Super-Kamiokande Collaboration

The Super-Kamiokande Collaboration consists of 236 members from 54 institutions.

Photo taken in the last collaboration meeting – May 2023

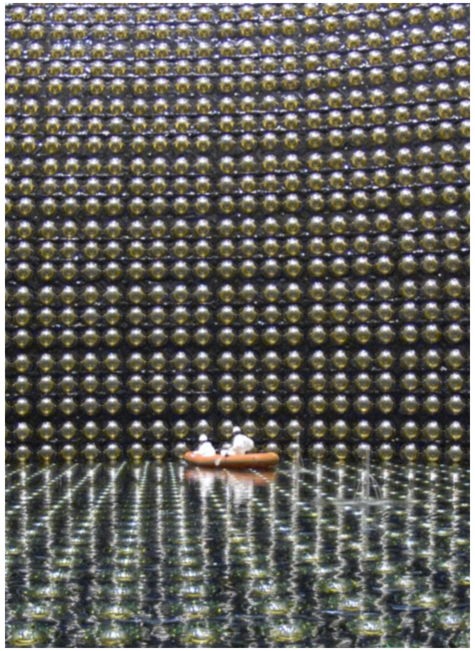
History of Super-Kamiokande

1996 | 2002 | 2006 | 2008 | 2019



SK-I, 1996-2001
11,146 ID PMTs
(with 40% coverage)

SK-II, 2002-2005
5,182 ID PMTs
(with 19% coverage + FPR)



SK-III, 2006-2008
11,129 ID PMTs
(again, 40% coverage)

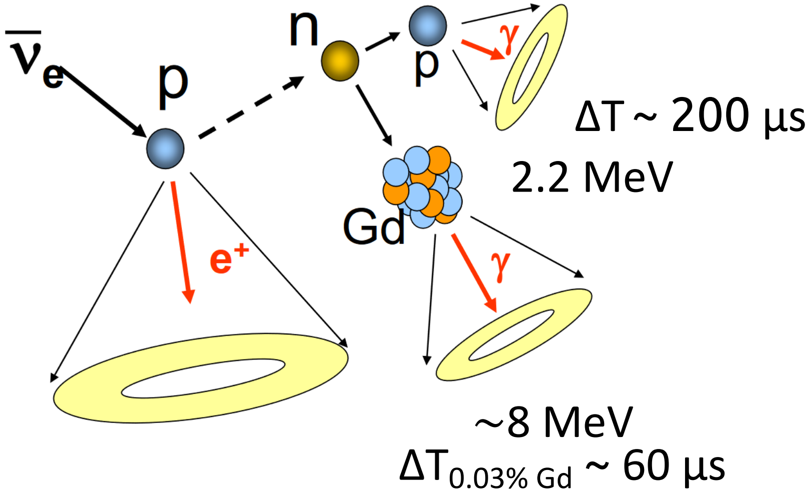
SK-IV, 2008-2018
11,129 ID PMTs
(upgraded electronics)

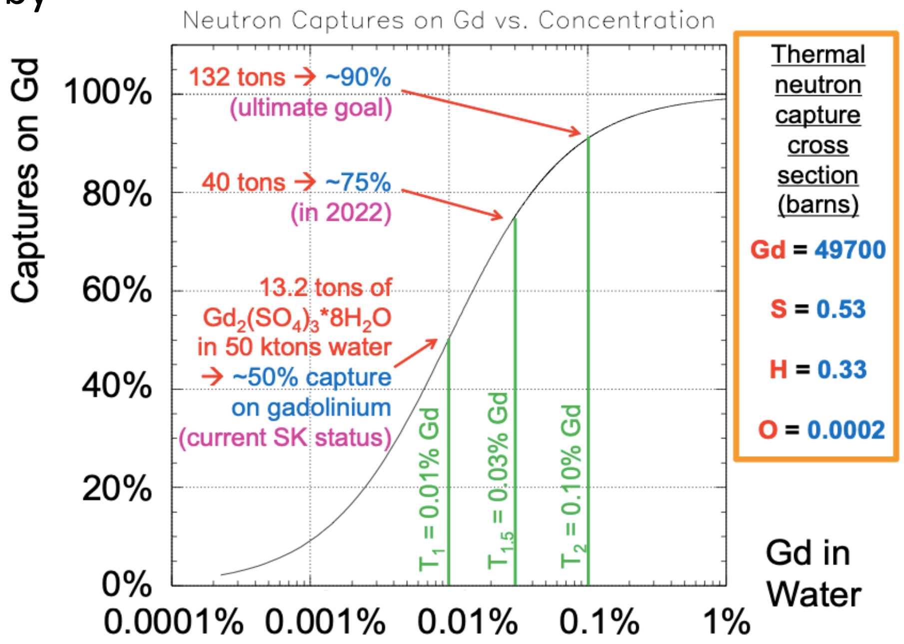
SK-V, 2019-2020
11,129 ID PMTs
(refurbished for Gd and with Hyper-K PMTs)

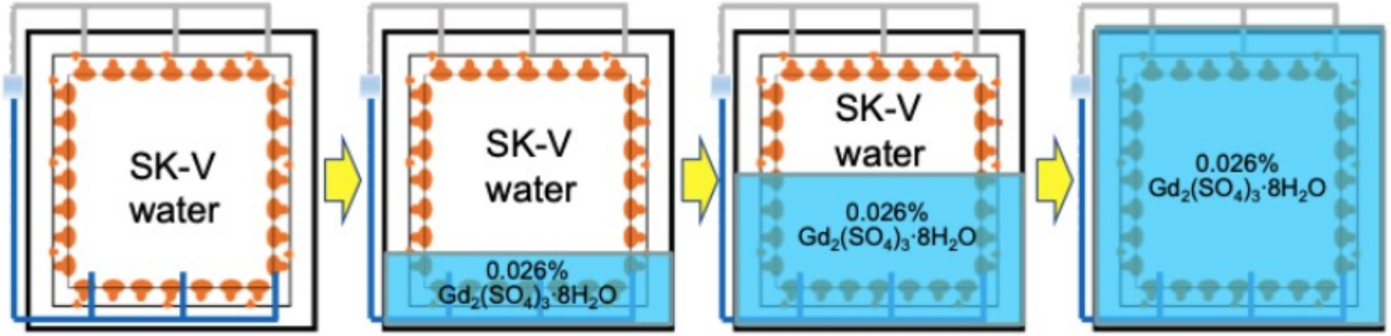
Super-Kamiokande with Gadolinium (SK-Gd)

Improve Super-Kamiokande's sensitivity to low energy electron anti-neutrinos by adding water-soluble gadolinium (Gd) salt to the water in the detector.

Isotope	neutron capture cross section
^{157}Gd	255,000 barns
^{155}Gd	61,000 barns
H	0.3 barn







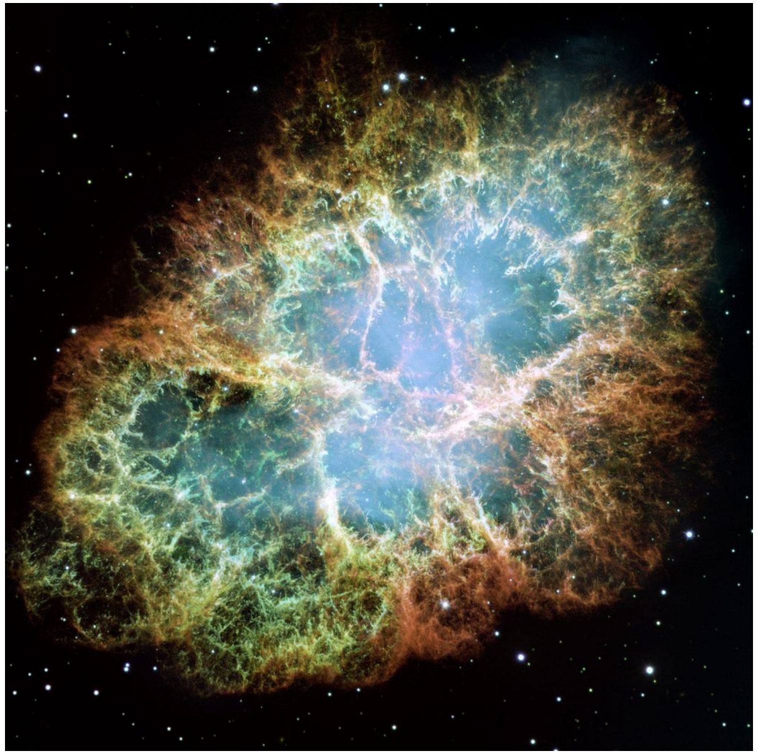
July/August 2020 → **13 tons $Gd_2(SO_4)_3$ * $8H_2O$**
0.01% Gd (SK-VI)

June/July 2022 → **40 tons $Gd_2(SO_4)_3$ * $8H_2O$**
0.03% Gd (SK-VII)

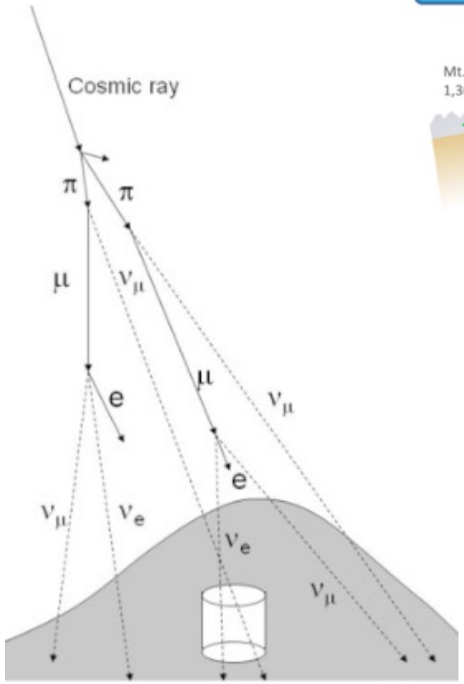
Beacom, Vagins PRL.93, (2004) 171101 **Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166248**

Super-Kamiokande – Physics Goals

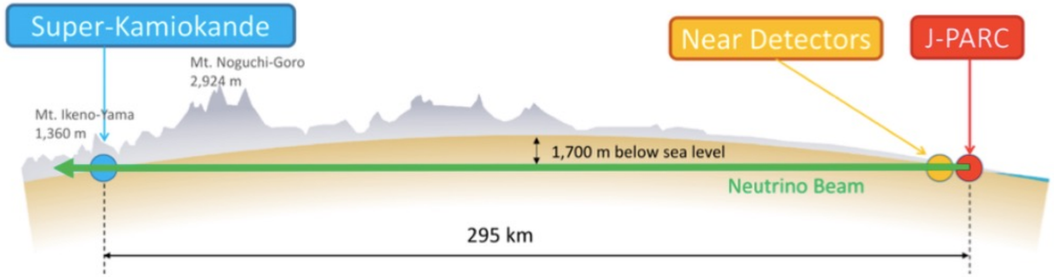
Super-Kamiokande is a multi-purpose observatory:
Solar neutrinos, Supernova neutrinos, Atmospheric neutrinos, Accelerator (T2K), Proton Decay, etc.



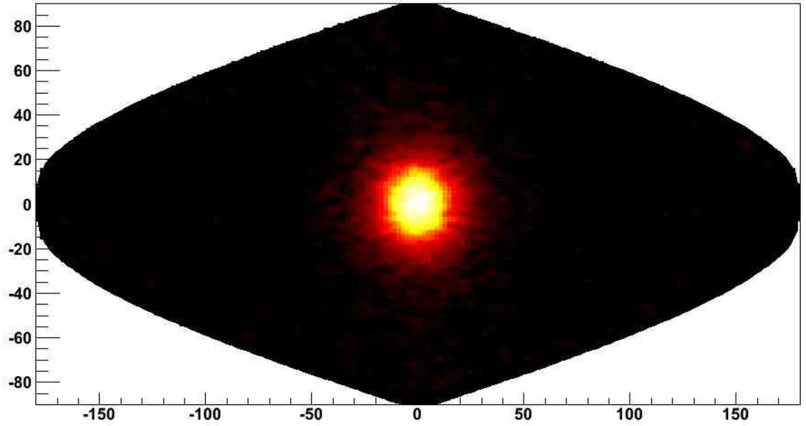
Supernova



Atmospheric neutrinos



T2K experiment scheme



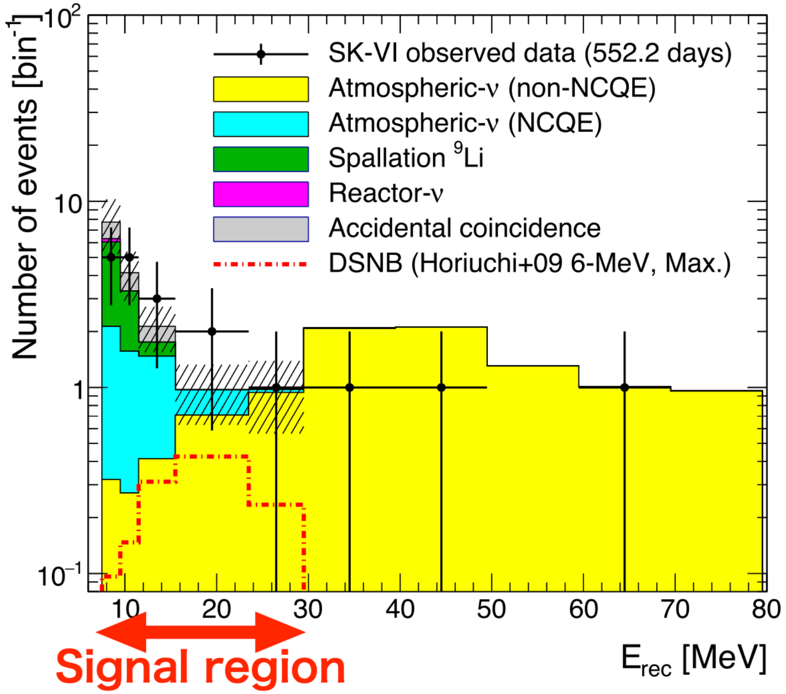
Sun seen with neutrinos

Super-Kamiokande – Physics Goals

Super-Kamiokande is a multi-purpose observatory:
Solar neutrinos, Supernova neutrinos, Atmospheric neutrinos, Accelerator (T2K), Proton Decay, etc.

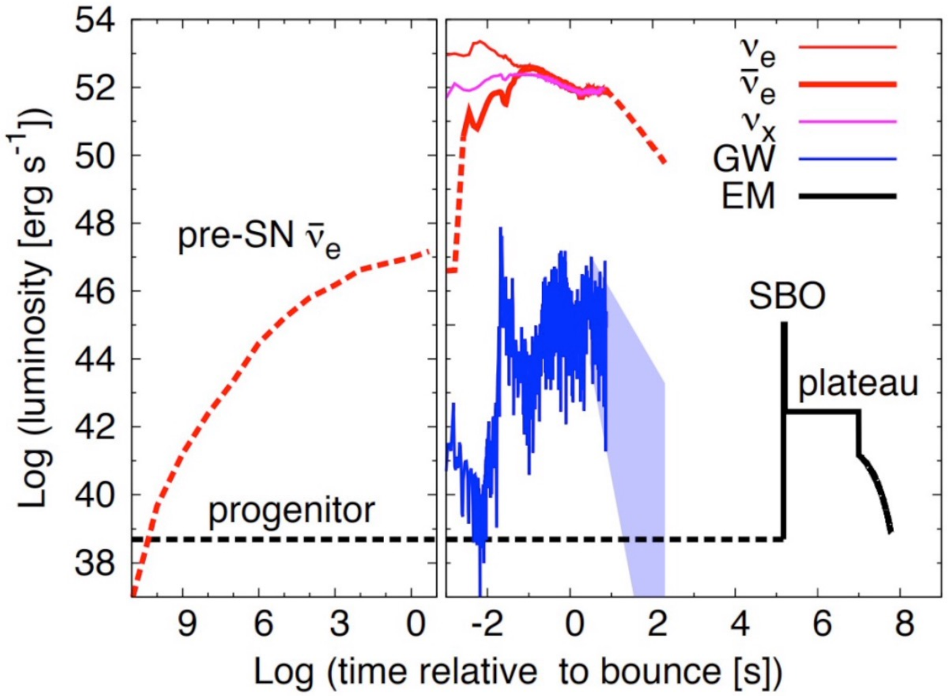
SK-Gd: Diffuse Supernova Neutrino Background (DSNB), Reactors and Pre-Supernova stars.

M. Harda et.al., ApJL. 951:L27 (2023)



DSNB search: five times smaller live time already shows comparable upper limit compared to pure water.

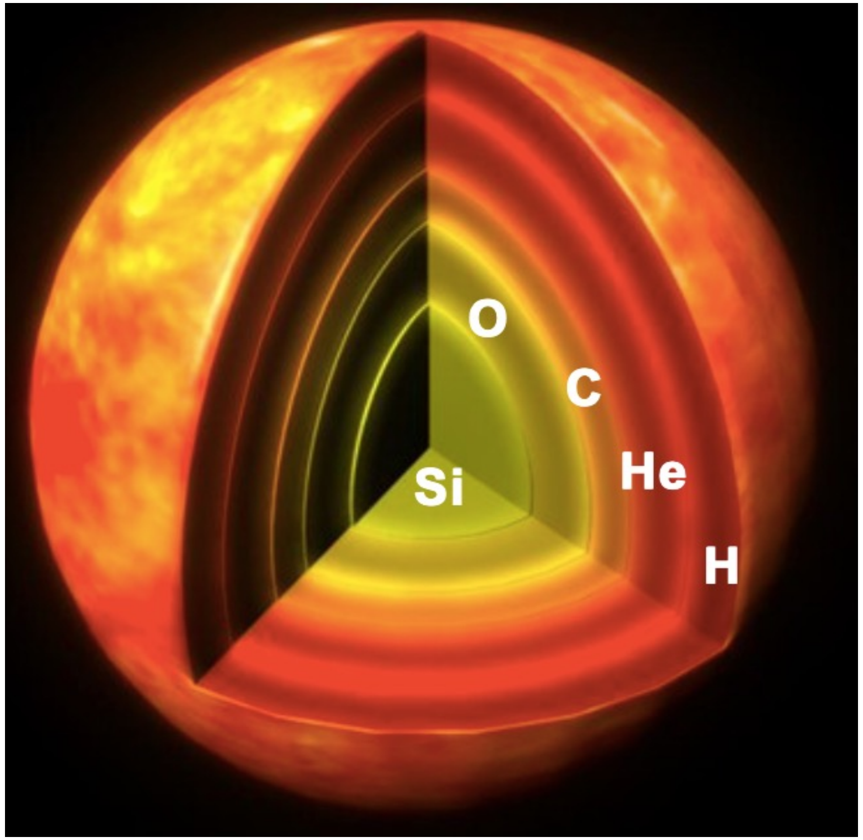
MNRAS, 461, 3296 (2016) arXiv:1602.03028



Pre-supernova: neutrinos emitted prior to core-collapse -> early warning for supernovae.

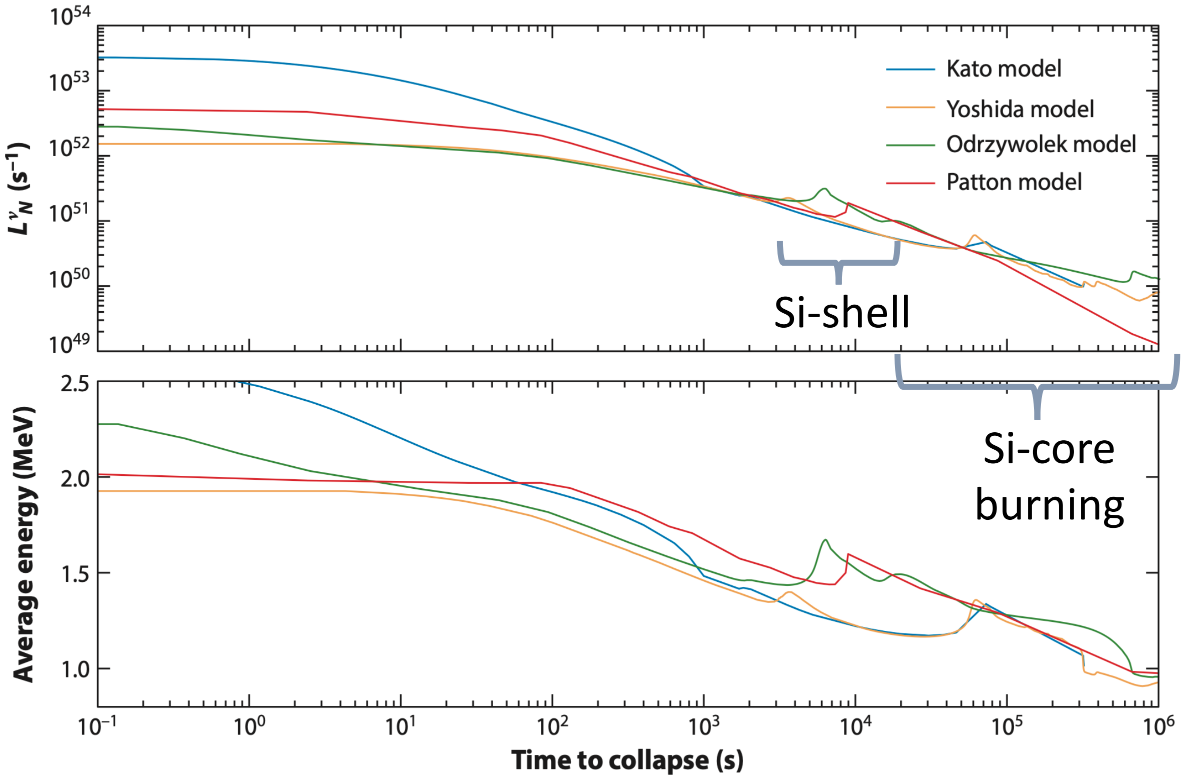
Pre-Supernova (Si-burning) Stars

The amount neutrino emission increases significantly as a massive star ($M > 8\ M_{\odot}$) approaches the core collapse supernova (CCSN) phase. After ignition of Carbon burning: **neutrino-cooling star**.



Neutrino luminosity $\sim 10^{12}\ L_{\odot}$
Photon luminosity $\sim 10^{5}\ L_{\odot}$

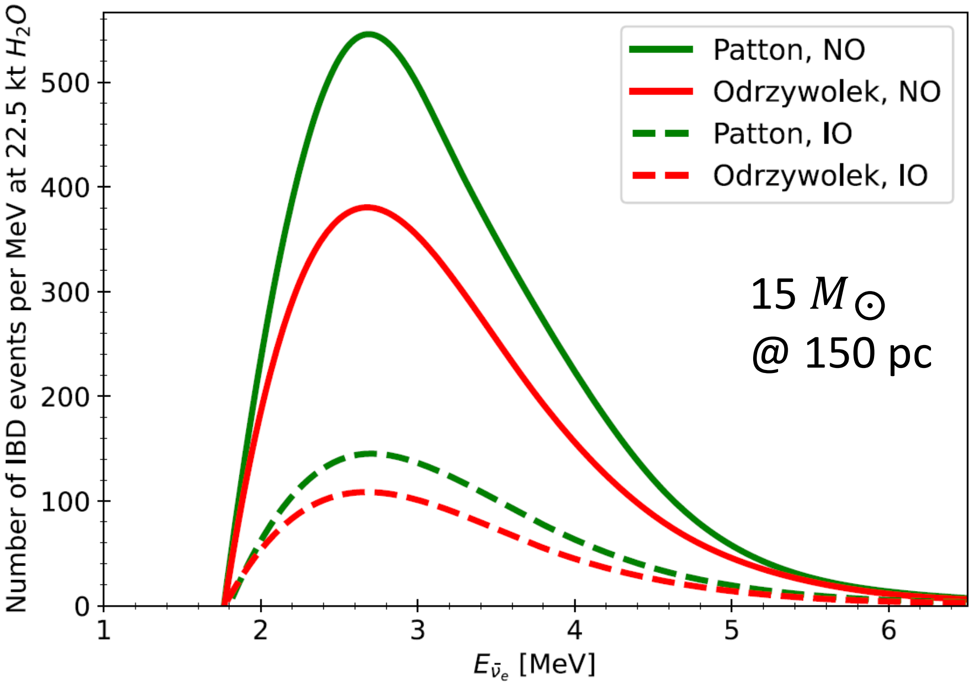
The last stage of these stars before the core-collapse is the **Si-burning** phase and it is expected to last for a **few days**.



Number luminosity (top) and average energy of $\bar{\nu}_e$ (bottom) as star approaches core collapse. From *Ann.Rev.Nucl.Part.Sci. 70 (2020) 121-145*

Pre-Supernova Neutrinos in SK-Gd

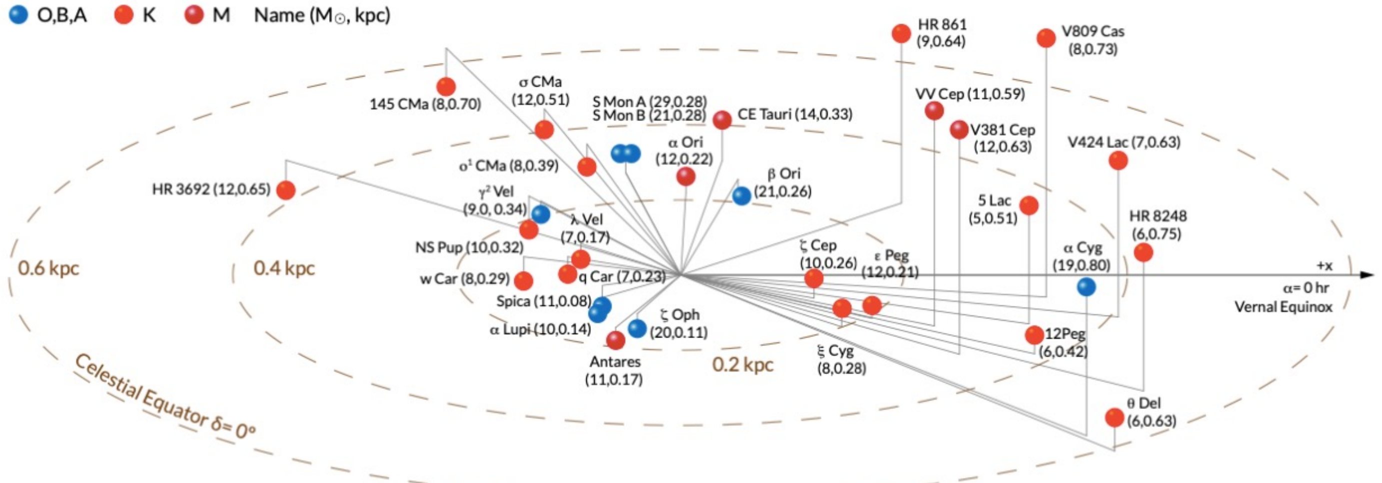
The neutrino production in pre-supernova (preSN) stars are mainly from electron-positron annihilation generating neutrinos and anti-neutrinos of every flavor. Nuclear weak processes such Beta Decay dominate near the core-collapse.



Number of pre-supernova IBD interactions in the 22.5 kt SK FV integrated over the last 10 hr prior to the CCSN as a function of the E_{ν_e} for normal neutrino mass ordering (solid) and inverted neutrino mass ordering (dashed). Models: Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611 and Patton, et al 2017 ApJ 851 6

The increased sensitivity for electron anti-neutrinos with the Gd loading allows Super-Kamiokande to be sensitive to pre-supernova stars.

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

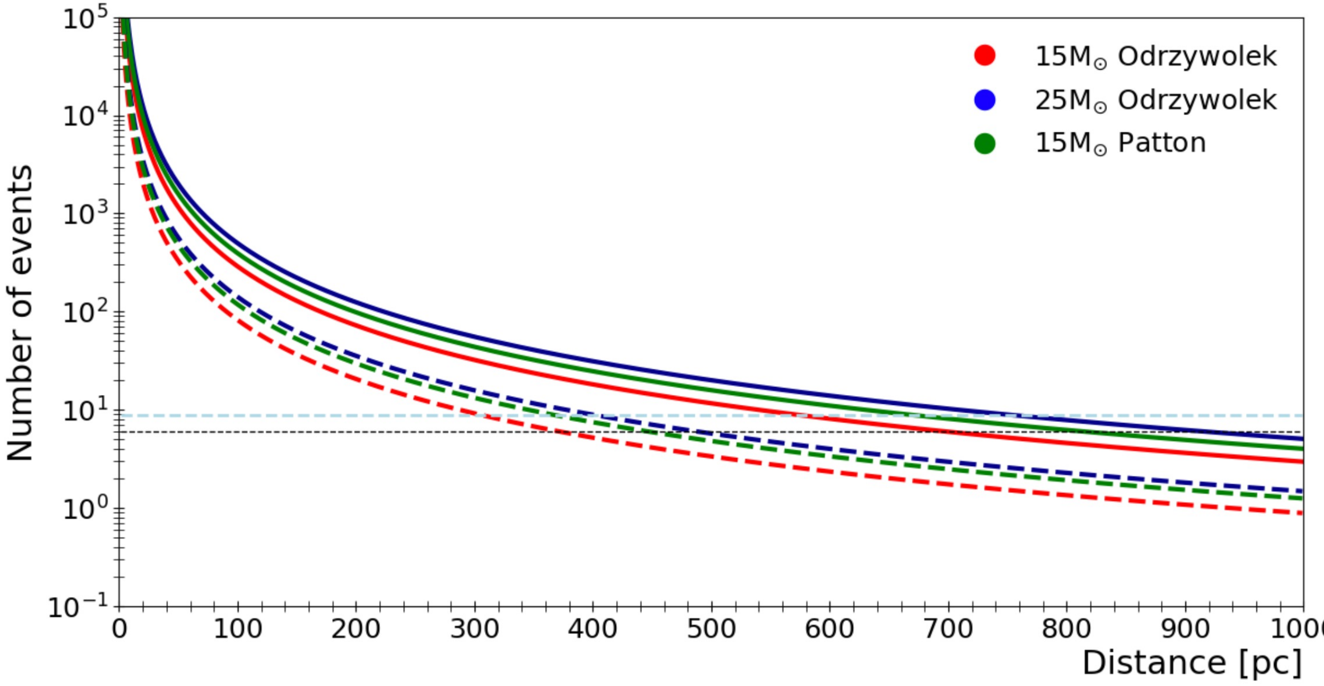


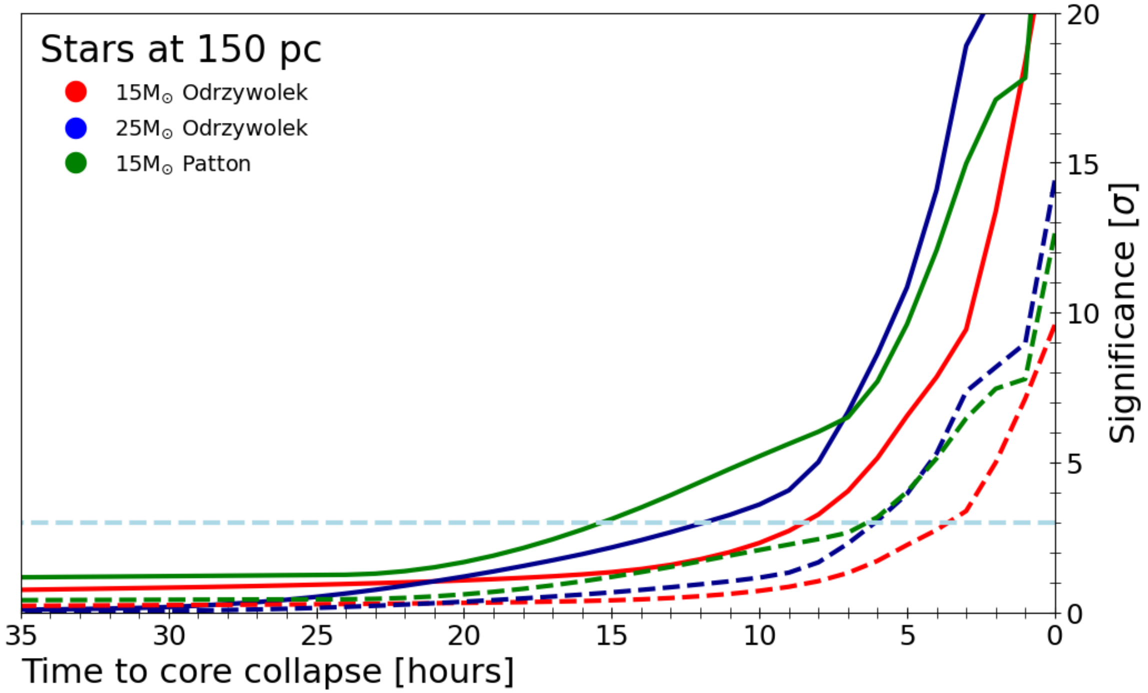
Mukhopadhyay, et al, 2020 ApJ 899 153

Sensitivity to pre-supernova neutrinos (0.03% Gd)

SK can detect preSN $\bar{\upsilon}_e$ via Inverse Beta Decay, selecting pairs of positrons and neutrons from the interaction based on their temporal/spacial correlation. Boosted Decision Tree is also used for selection (L. N. Machado *et al* 2022 *ApJ* 935 40)

Main background sources: reactor neutrinos, geoneutrinos, radioactive decays and fake IBD events (accidental).



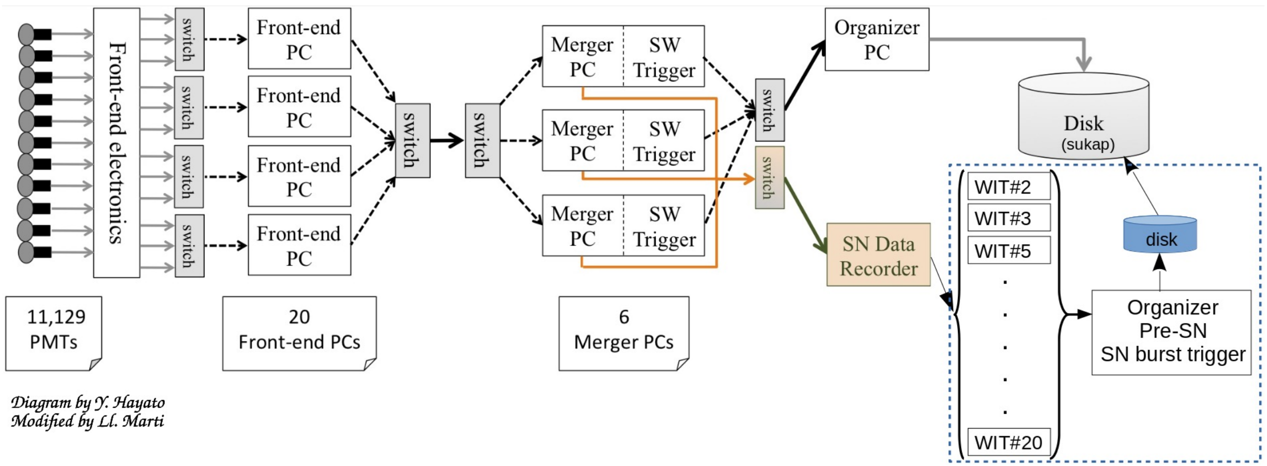


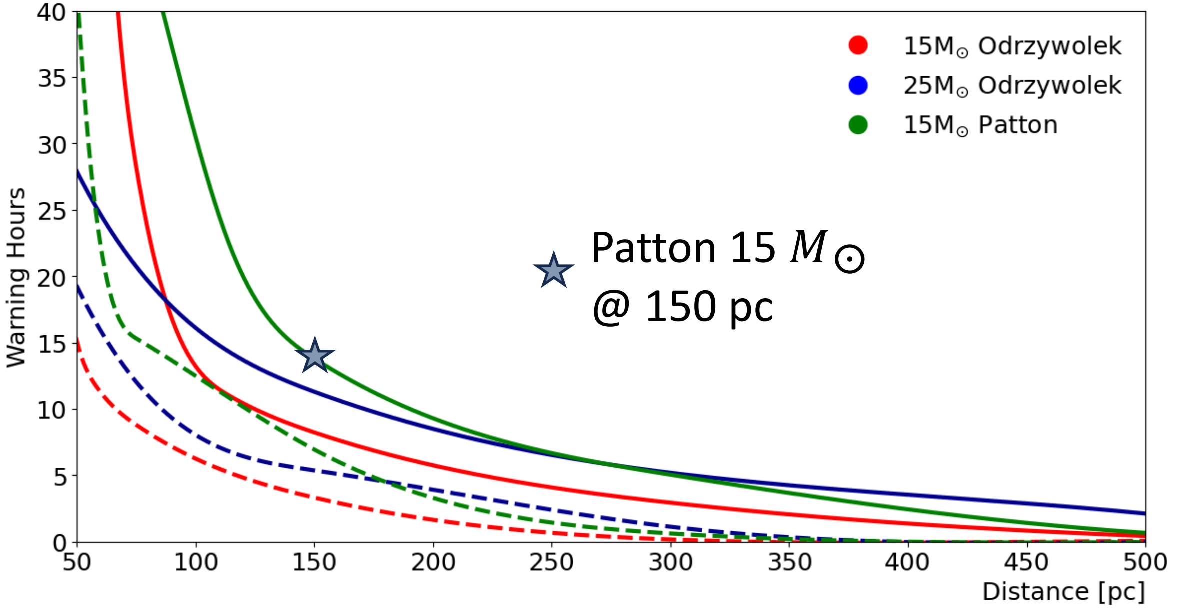
(a) Expected number of IBD events for difference distances and (b) evolution of the significance level in Super-Kamiokande with 0.03% Gd as a massive star (d = 150 pc) approaches core-collapse. Solid lines show normal neutrino mass hierarchy and dashed lines show inverted neutrino mass hierarchy. The considered fluxes are evaluated for stars with 15 $M_\odot$ and 25 $M_\odot$ (Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611 and Patton, et al 2017 ApJ 851 6).

Pre-Supernova Alert System

An early warning system for supernovae based on the search for pre-supernova neutrinos is running in Super-Kamiokande since **October 22nd, 2021.**

The system is integrated to the independent trigger Wide-band Intelligent Trigger (WIT). Data is received by the system immediately after acquisition and fast reconstruction online.



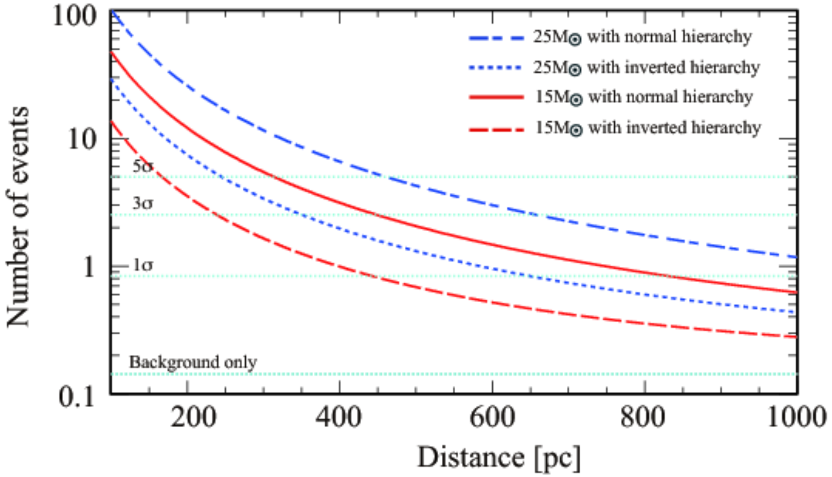


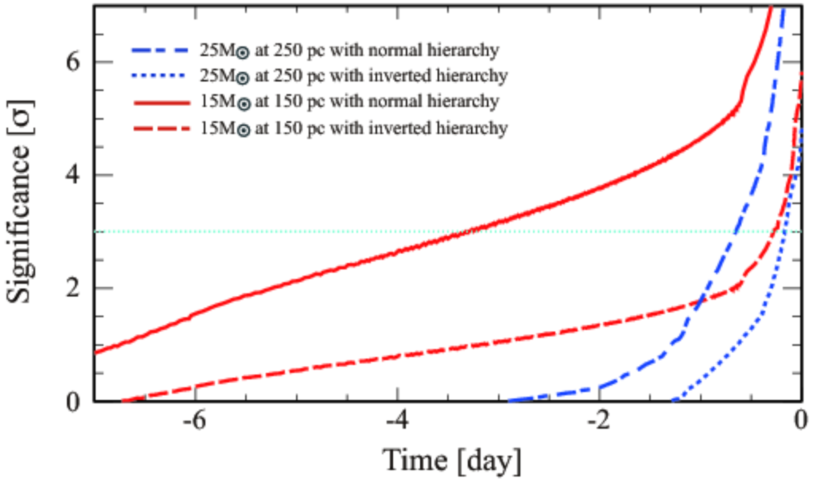
Expected warning hours as function of distance for a 3σ detection by the pre-Supernova alert system for Super-Kamiokande with 0.03% Gd. Solid lines show normal neutrino mass hierarchy and dashed lines show inverted neutrino mass hierarchy.

After following the same processes as the standard preSN analysis, the detection significance is calculated, and an alarm decision is made.

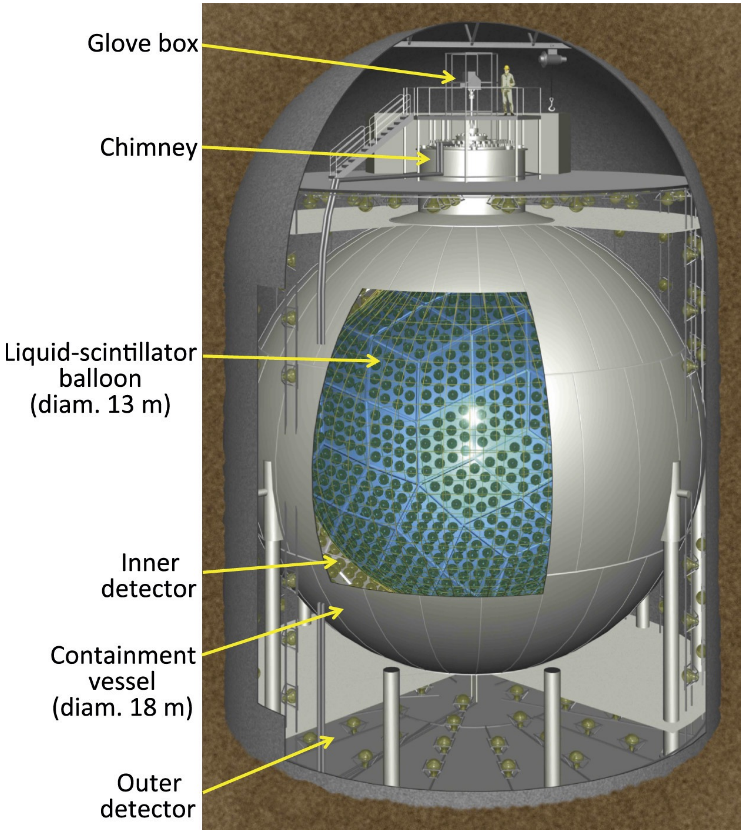
Combined SK and KamLAND preSN Alarm

The Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) experiment also has an active running pre-supernova alarm, with very low energy threshold and low background rates.





Expected number of IBD events before core collapse and time evolution of significance for Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611. From *Astrophys.J.* 818 (2016) 1, 91

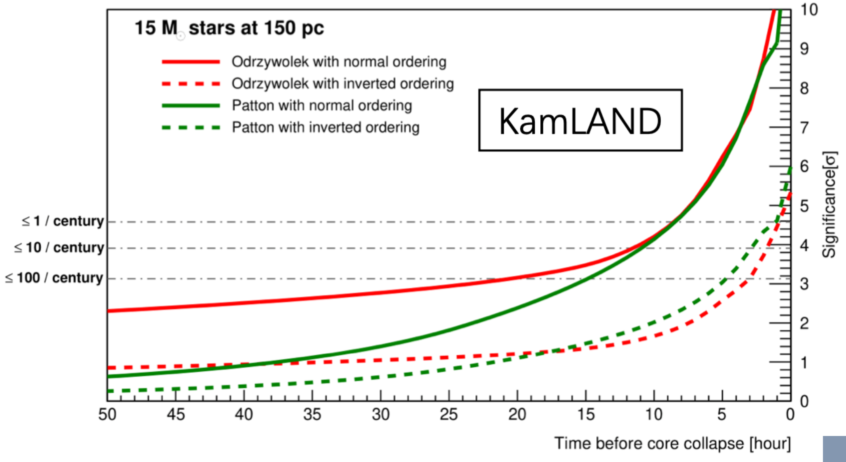


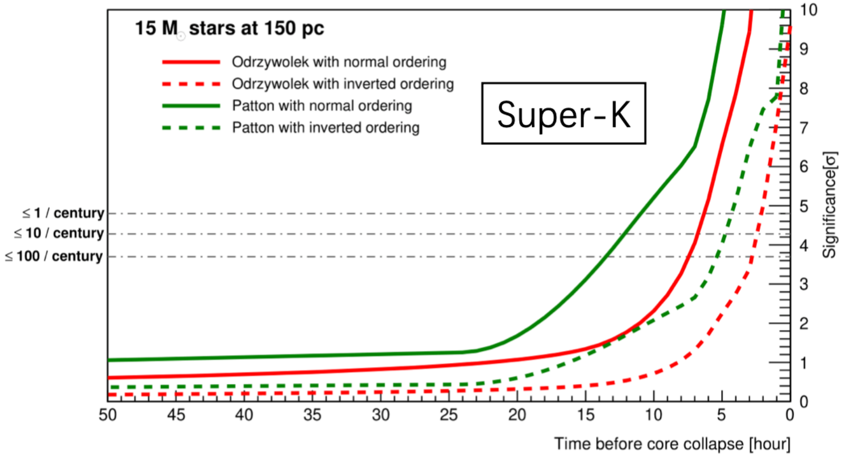
The KamLAND detector. From *Nucl.Instrum.Meth.A* 769 (2015) 88-96

There has been an agreement between Super-Kamiokande and KamLAND to combine both pre-supernova alarms.

Combined SK and KamLAND preSN Alarm

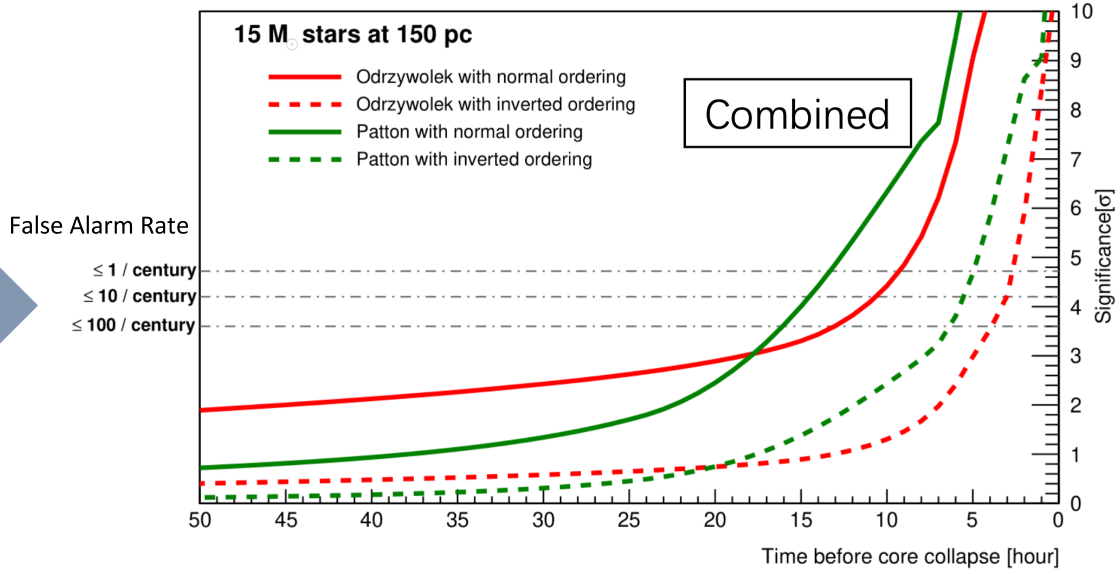
The pre-supernova combined alarm uses the local results from both experiments to calculate a common significance level.





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

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



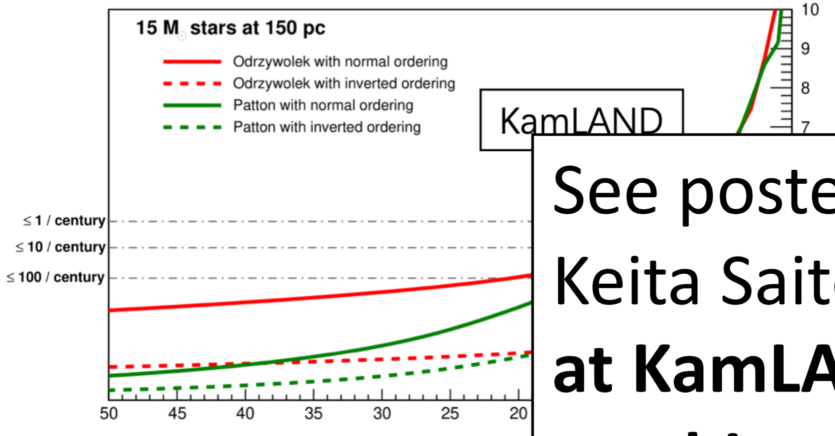
If detection significance below 1 FAR/century: GCN circular

False Alarm Rate (FAR): frequency of false alarms based on current background levels.

System is now launched and open to public:
https://www.lowbg.org/presnalarm/

Combined SK and KamLAND preSN Alarm

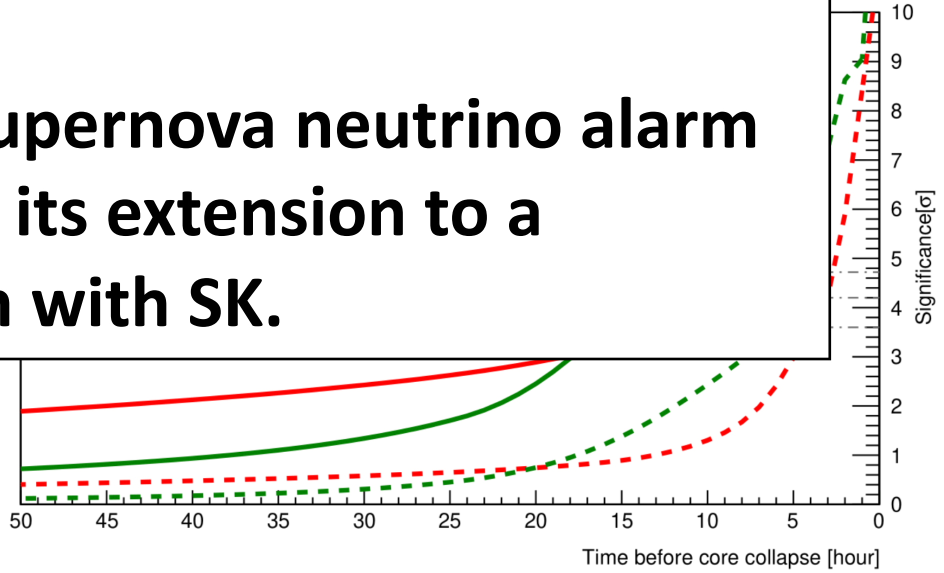
The pre-supernova combined alarm uses the local results from both experiments to calculate a common significance level.



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

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

See poster:
Keita Saito, **Pre-supernova neutrino alarm at KamLAND and its extension to a combined system with SK.**



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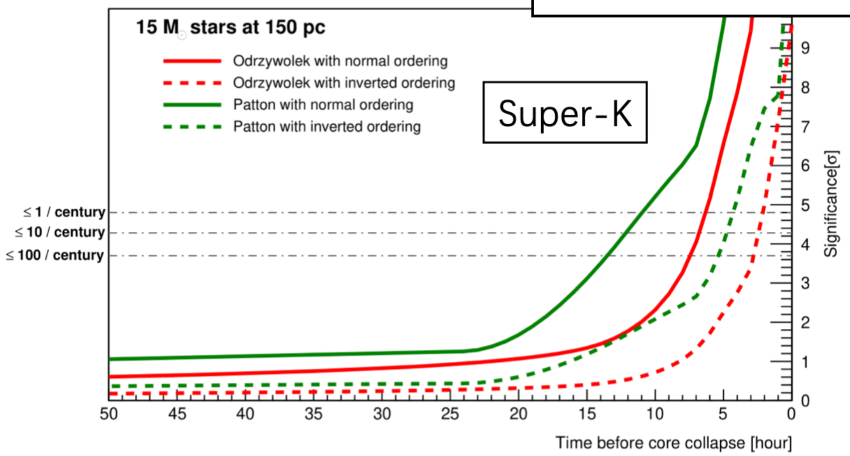


False Alarm Rate (FAR): frequency of false alarms based on current background levels.

System is now launched and open to public: https://www.lowbg.org/presnalarm/

Outlook

- Super-Kamiokande is a neutrino observatory running since 1996. In 2020, the experiment started the SK-Gd phase, in which gadolinium was added to the water in the detector to increase its sensitivity to low energy $\bar{\upsilon}_e$. Currently SK-Gd has a concentration of 0.03% Gd by mass;
- The enhanced sensitivity of SK-Gd to low energy $\bar{\upsilon}_e$ opened the possibility for the detection of yet-unobserved neutrinos from different astronomical sources such as pre-supernova stars;
- Neutrinos from pre-supernova stars (Si-burning phase) can be currently detect in SK-Gd, could potentially give evidence for neutrino mass hierarchy and help with the distinction of stellar evolution models;
- Their detection can also give early warnings for potential supernovae, which showed the possibility of developing a pre-supernova alarm for Super-Kamiokande;
- The pre-supernova alarm has been running in Super-Kamiokande since October 22nd, 2021. For 0.03% Gd, it can give alerts to Betelgeuse over 10 hours before the core-collapse supernova;
- The combined Super-Kamiokande and KamLAND preSN alarm has been launched. It is open to public, and results will soon be included to GCN (https://www.lowbg.org/presnalarm/).

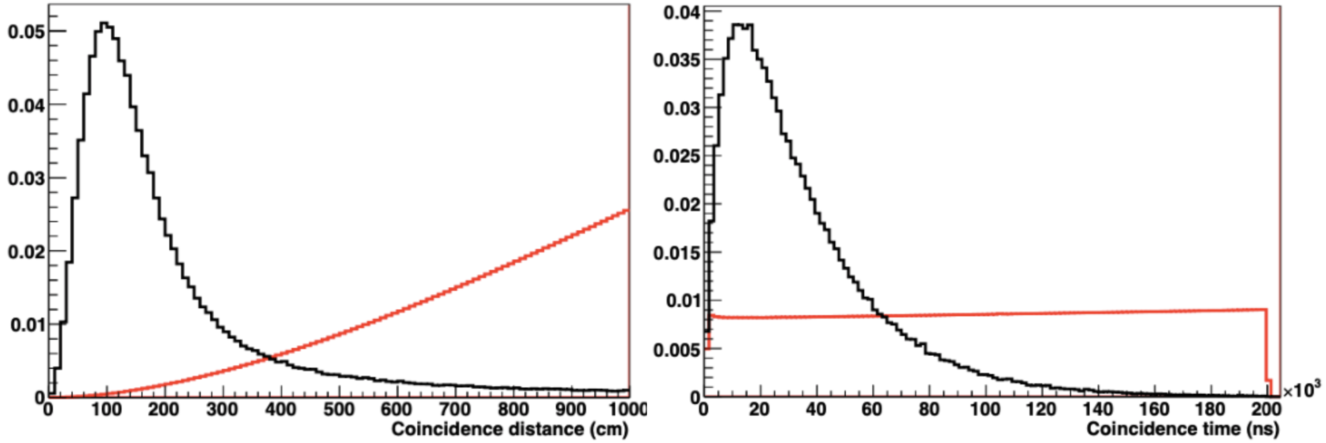
BACKUP

Pre-supernova Alarm – Selection

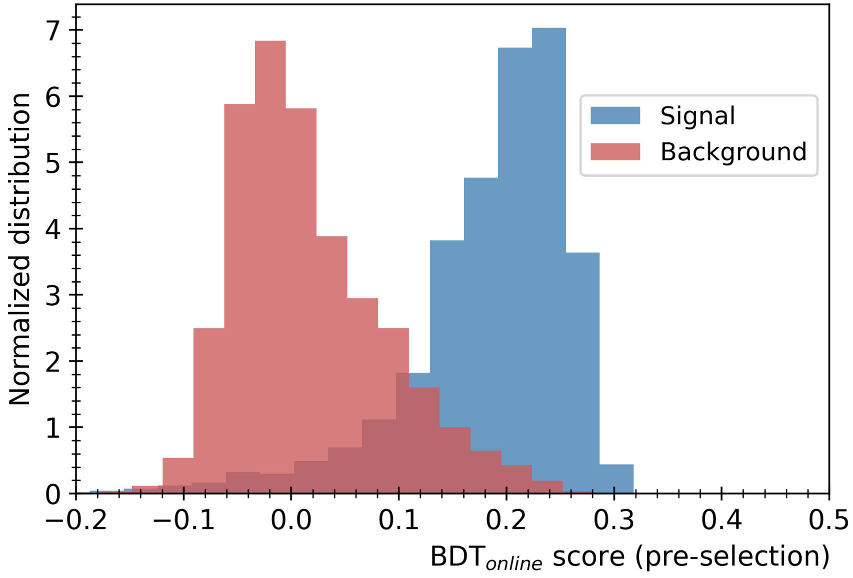
Mainly based on dR, dT and BDT. Regularly updated to consider the detector conditions.

Inputs and parameters (BDT):

- Parameters: number of trees = 1000, Adaboost, learning rate = 0.5, minimum events at leaf = 5%.
- Pre-selection BDT (BDT_{online}): trained based only on the variables available fast online vertex reconstruction;
- Final selection BDT: based on the angular distribution of hits, reconstructed energy, and quality, and distance from events to the detector wall.



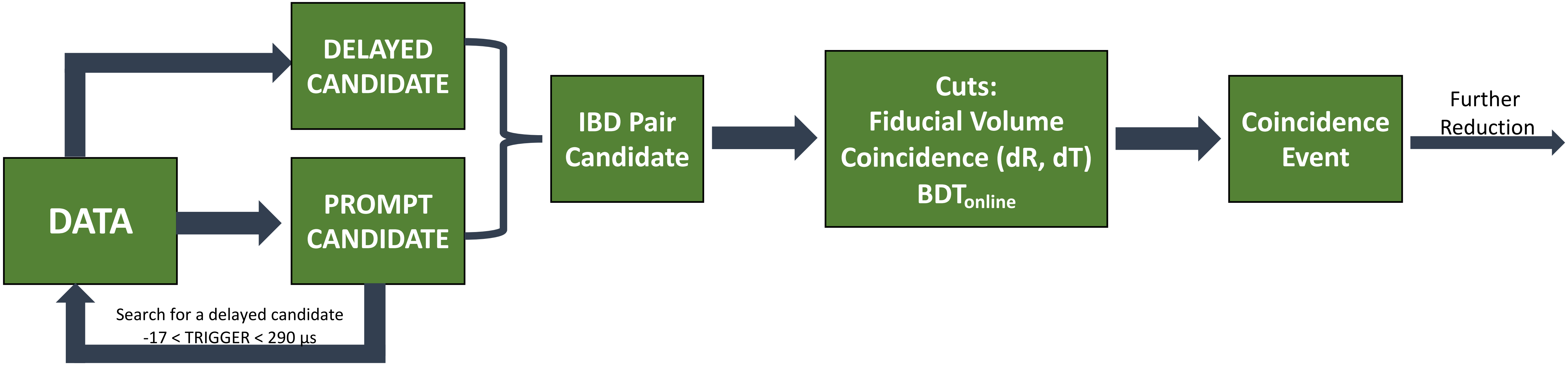
Coincidence Time and Distance between products from IBD events for simulated signal (black) and background (red).



Pre-supernova Alarm – Selection

The BDT_{online} not only allows faster processing time, but also effectively remove busts of IBD-like event, which are presumably from spallation.

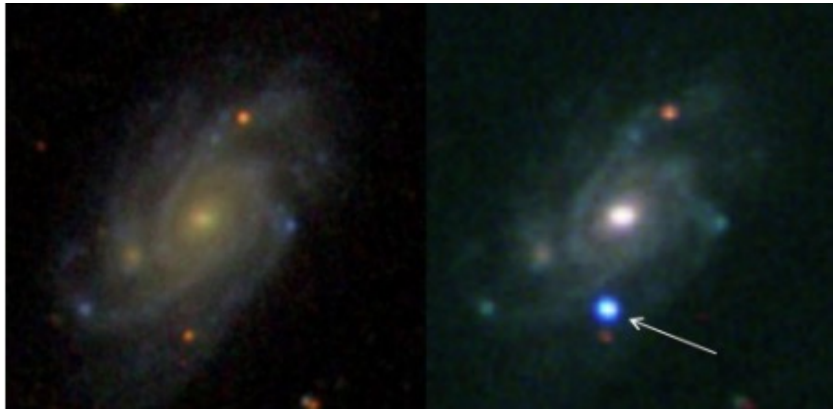
Search for Coincidence Events:



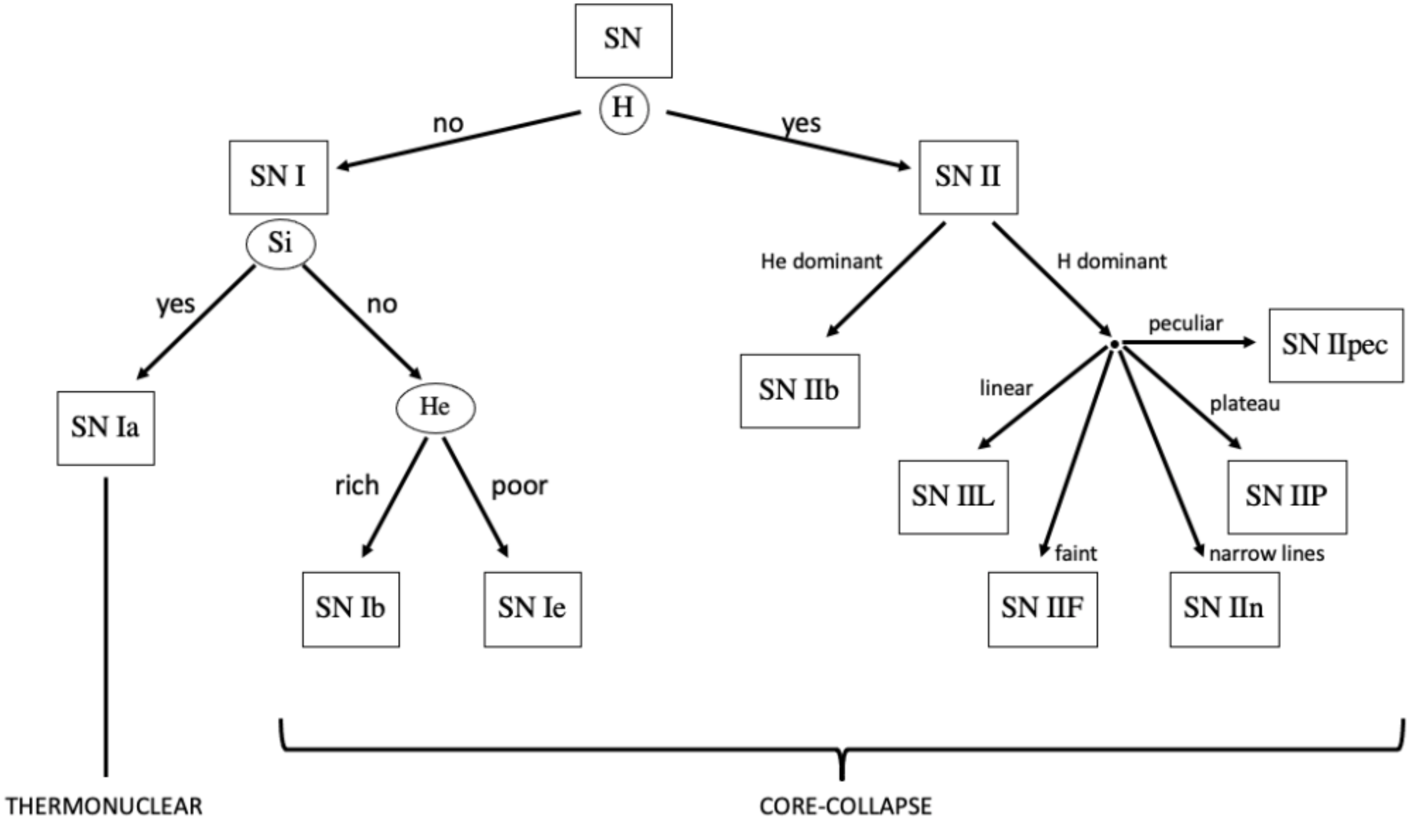
The BDT_{online} also improved the sensitivity for the pre-Supernova detection.

Supernovae

A core-collapse Supernova occurs at the end of the life of a massive star, which is a star with at least eight solar masses, when the core of the star goes through a gravitational collapse. This process releases an energy of $\sim 10^{53}$ ergs, in which about 99% is released by neutrinos.



After the explosion, this energy spreads through the universe, which is fundamental for the evolution of galaxies, planets, and other stars, making the Supernova phenomena an object of huge interest to cosmology.



Supernova Classification

Supernovae

The high density of inner core traps neutrinos, which are further released in form of neutrino-spheres for different neutrino flavors, as they interact differently with matter. These neutrinos are produced through different processes in the inner core.

$$e^- + e^+ \rightarrow \nu_x + \bar{\nu}_x$$

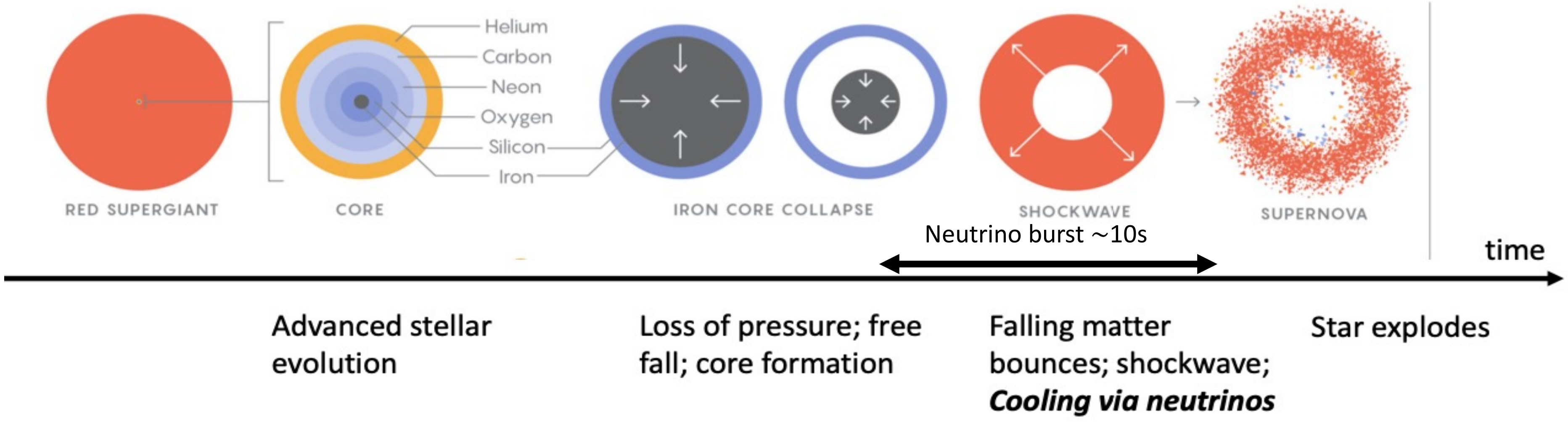
$$e^\pm + N \rightarrow e^\pm + N + \nu_x + \bar{\nu}_x$$

$$\gamma \rightarrow \nu_x + \bar{\nu}_x$$

$$N + N \rightarrow N + N + \nu_x + \bar{\nu}_x$$

$$\gamma + e^\pm \rightarrow e^\pm + N + \nu_x + \bar{\nu}_x$$

These interactions in the dense core produces pairs of neutrino and anti-neutrinos from all three flavours. It is produced around $3{\times}10^{53}$ ergs of gravitational energy, in which 99% goes into neutrinos, 0.01% into photons, and 1% into kinetic energy ejecting material.

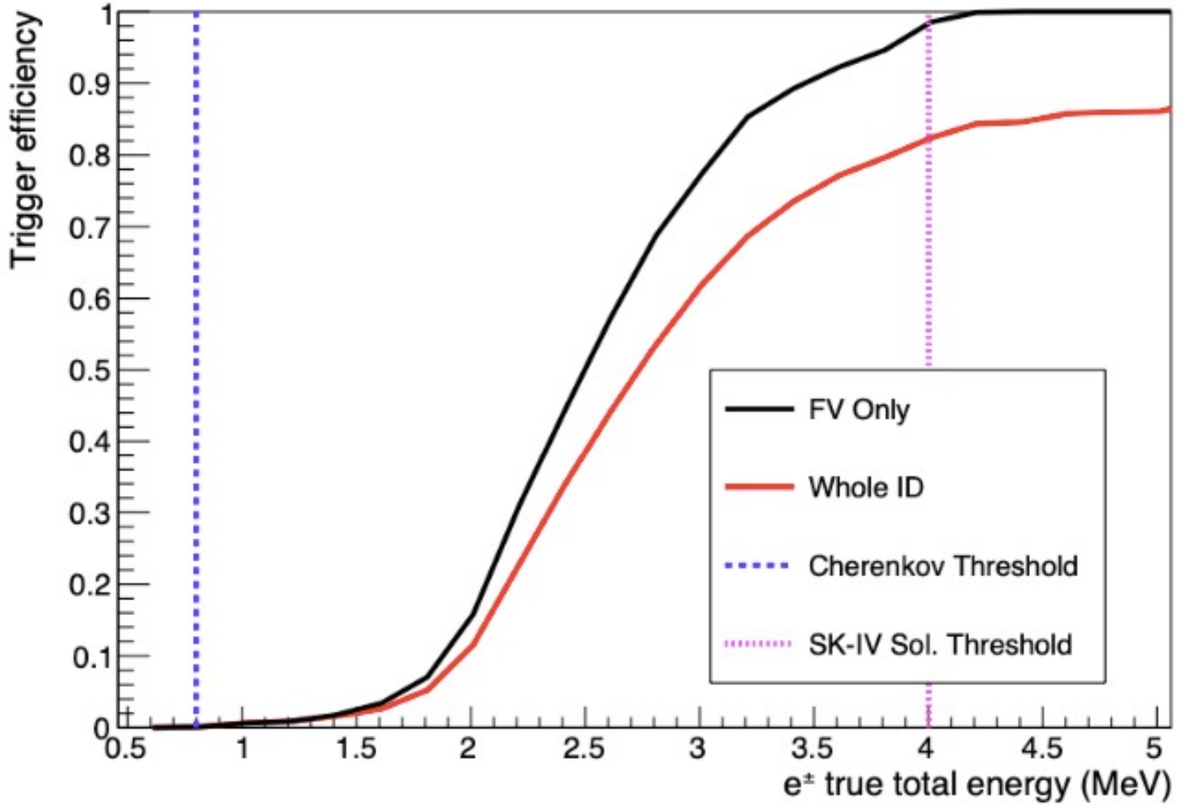


Wide-band Intelligent Trigger (WIT)

WIT is a system designed to extend the sensitivity of SK to lower energy events using parallel computing to reconstruct vertices in real time, discarding events that are not well reconstructed or very close to the walls of the detector. The WIT system consists of more than 400 hyper-threaded cores spread over many online computers that work in parallel with each other.

WIT does not apply any threshold to the minimum number of hits recorded by the PMTs. The system was design to process all acquired data, extracting and reconstructing very low energy events with efficiency close to 100% in real time, with the use a great amount of parallel computing.

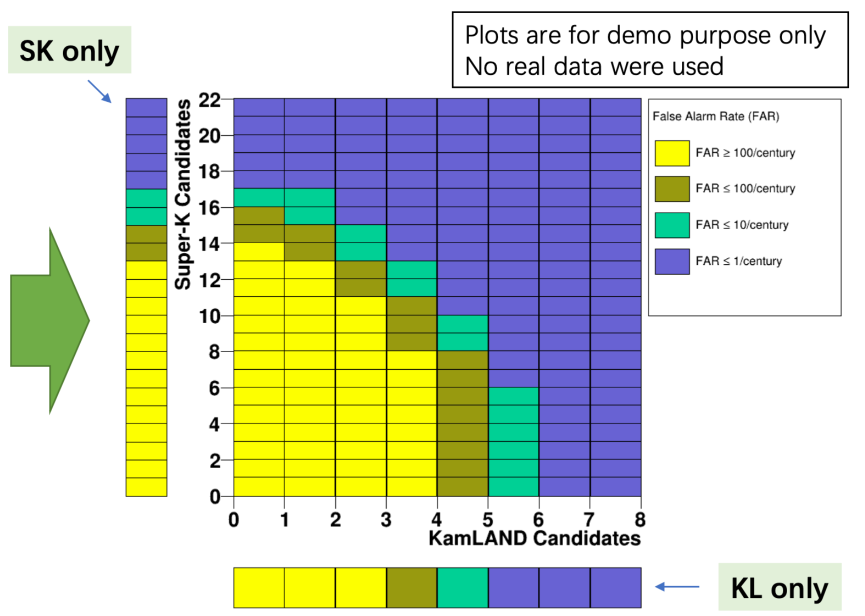
The WIT system receives raw data blocks containing about 23 milliseconds of data each from data acquisition machines; these blocks are then distributed to the ten online computers to search for signals (11 PMT hits within 230 nanoseconds) above expected dark noise levels (12 hits) inside these blocks.



WIT trigger efficiency

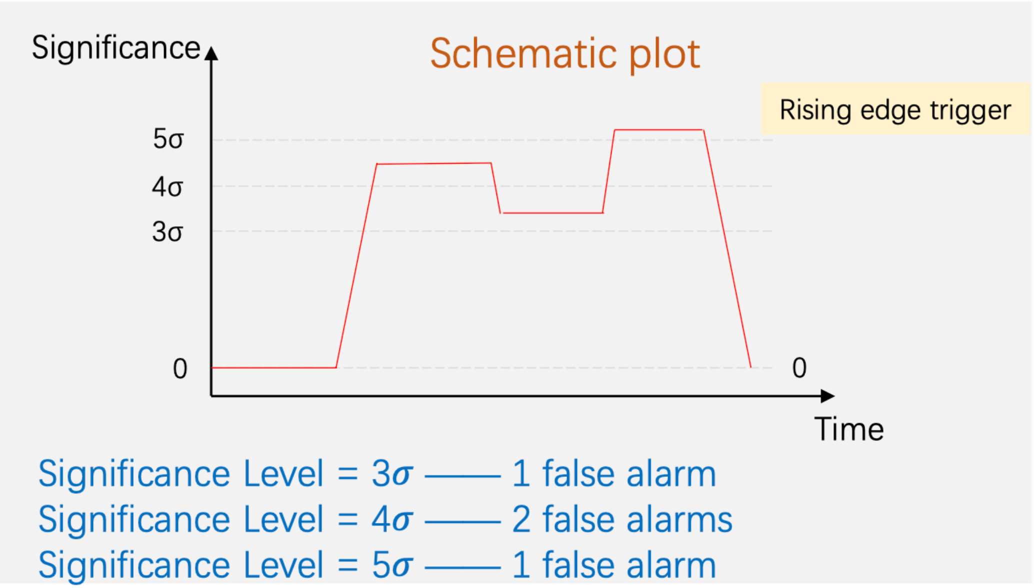
Combined Alarm

False Alarm Rate



- **Difficulties** in interpreting the significance to the false positive rate.
  - Significance level = 3σ **doesn't** mean the false positive rate = 0.3% !
- Reasons:
  - **NOT independent** measurements:
    -SK collects candidates in a 12-hour time window and updates every ~5 min, while KamLAND does in a 24-hour window.
  - The "**Look Else-where Effects**"

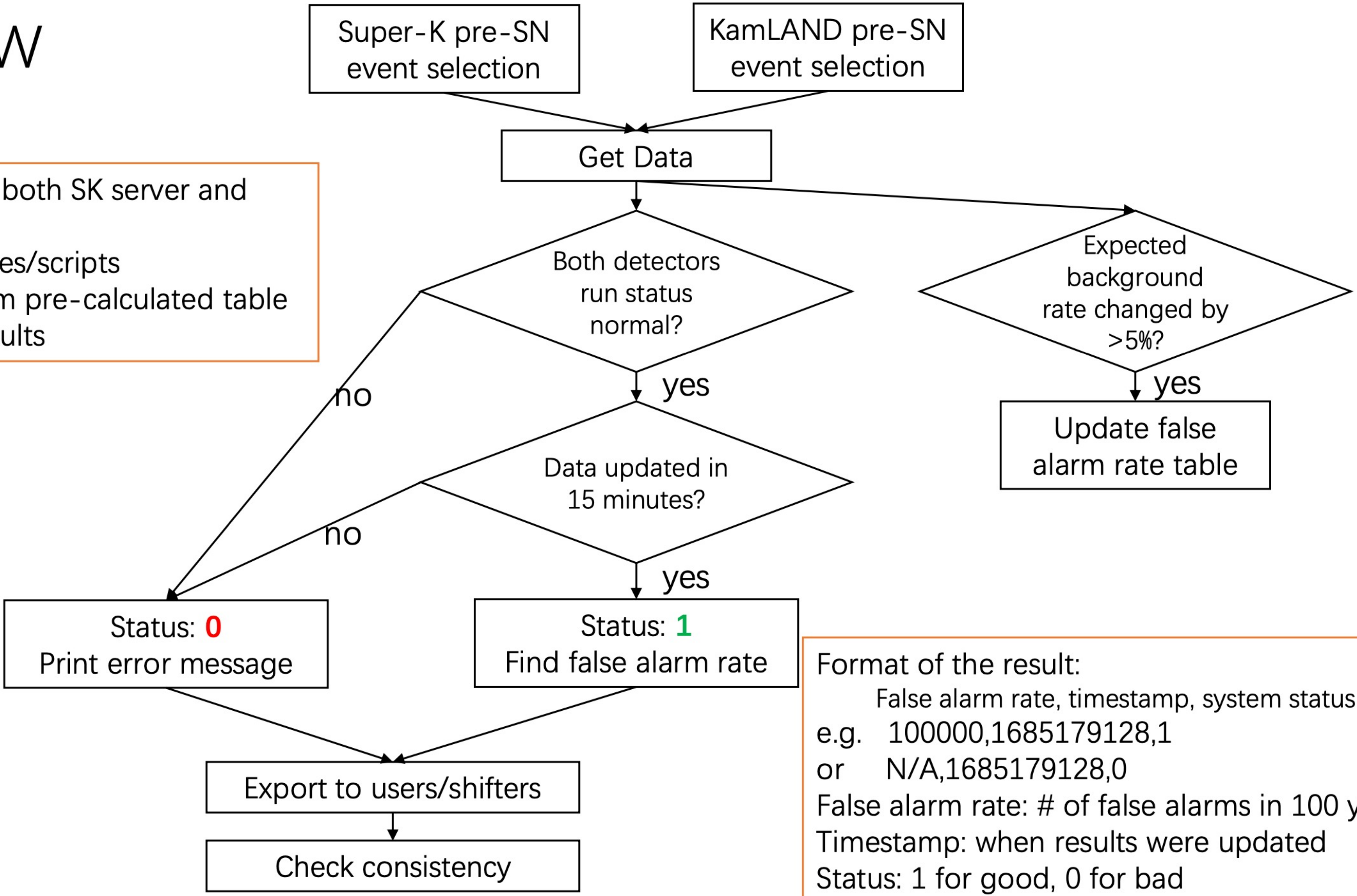
- **"False Alarm Rate"** extracted from toy Monte-Carlo
  1. Generate a time-series of random events assuming background-only for 1 million years
  2. Find the combined significance for each 5-minute time slot (the online combined alert updates every 5 min)
  3. Count how many false positives assuming a certain significance level.



Combined Alarm

Workflow

Combined alert running on both SK server and KamLAND servers
- Essentially the same codes/scripts
- Find false alarm rate from pre-calculated table
- Check consistency of results



Format of the result:
False alarm rate, timestamp, system status
e.g. 100000,1685179128,1
or N/A,1685179128,0
False alarm rate: # of false alarms in 100 yr
Timestamp: when results were updated
Status: 1 for good, 0 for bad