XXI Workshop on Neutrino Telescopes

Enhancing Low-Energy Neutrino Sensitivity in Super-Kamiokande with the Wide-band Intelligent Trigger

September 30th, 2025

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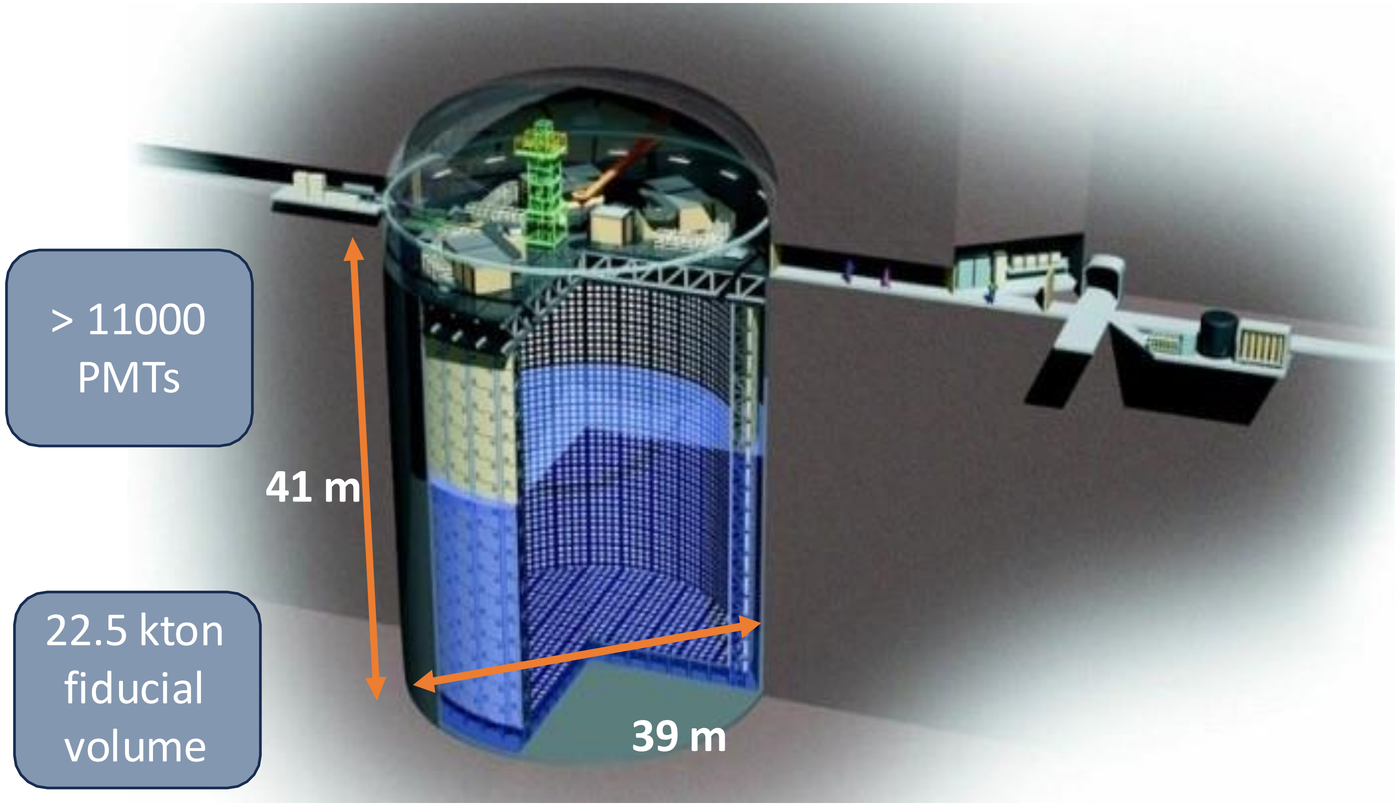
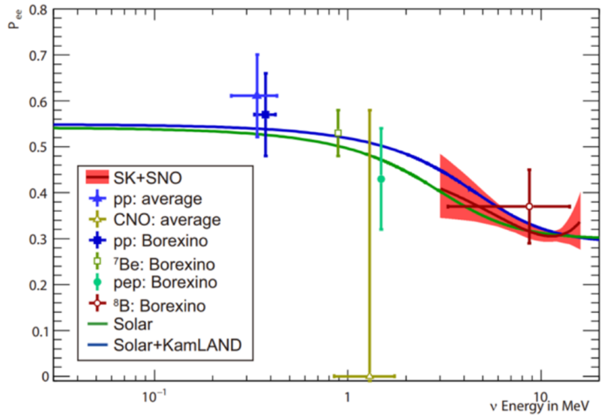
The Super-Kamiokande Experiment

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.



Physics in the low-energy regime (< 4 MeV):

- Access to the full solar neutrino spectrum (pp, ^{7}Be, CNO) → Upturn in the electron neutrino survival probability expected at lower energies.



- Search for astrophysical neutrinos, not yet observed.
- Signals from reactor / geo-neutrinos also sit in the few-MeV window.

Super-Kamiokande is unique in covering neutrinos from MeV solar energies to TeV cosmic rays, while probing rare processes like nucleon decay.

Accessing those energies promises new constraints on solar models, neutrino spectra, supernova physics, and star formation histories.

The Wideband Intelligent Trigger (1)

Pushing traditional triggers hit threshold down to reach < 4 MeV causes huge fake rates from dark noise + radioactivity → DAQ/bandwidth blow-ups.

Online reconstruction is the key discriminator

- Reconstruct and preform vertex reconstruction of recorded hits in real time → reject random/noise hits before they look like an event.
- Keep efficiency while suppressing fake triggers at lower energies.
- Use parallel computing to keep up in real time

The Wide-band Intelligent Trigger (WIT) has been developed to simultaneously trigger and reconstruct very low energy electrons (above 2.49 kinetic MeV) with an efficiency close to 100%.

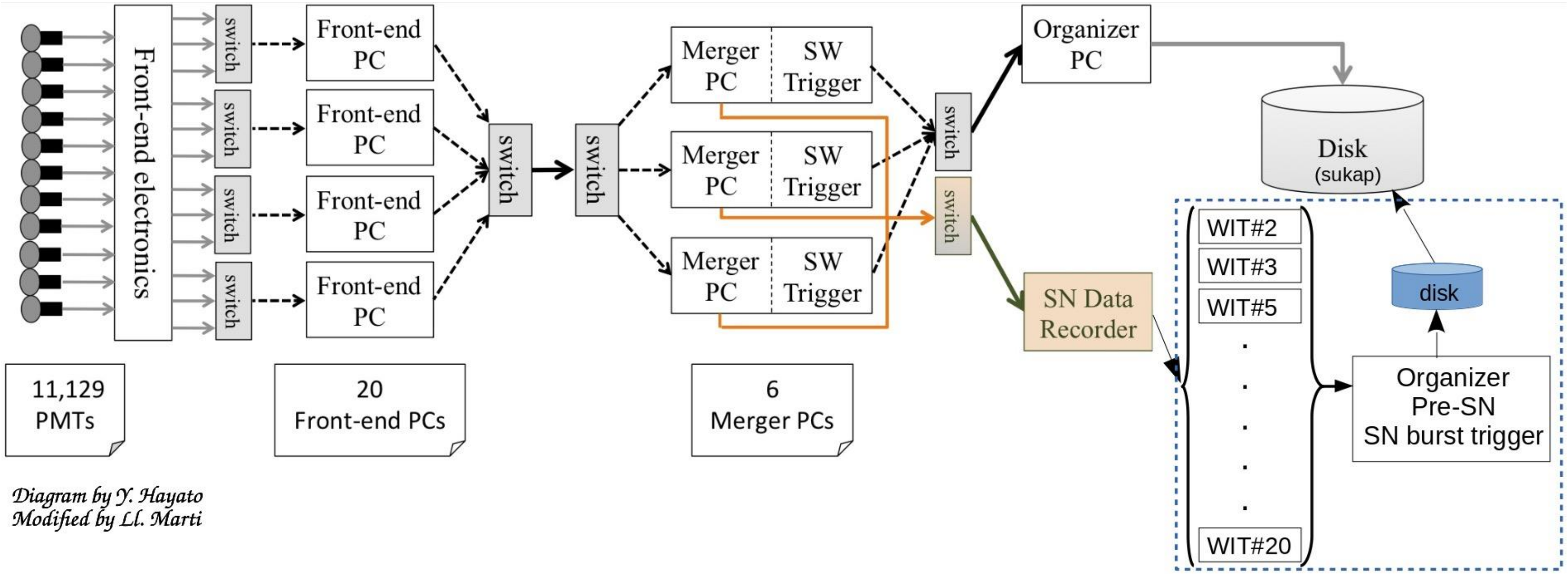
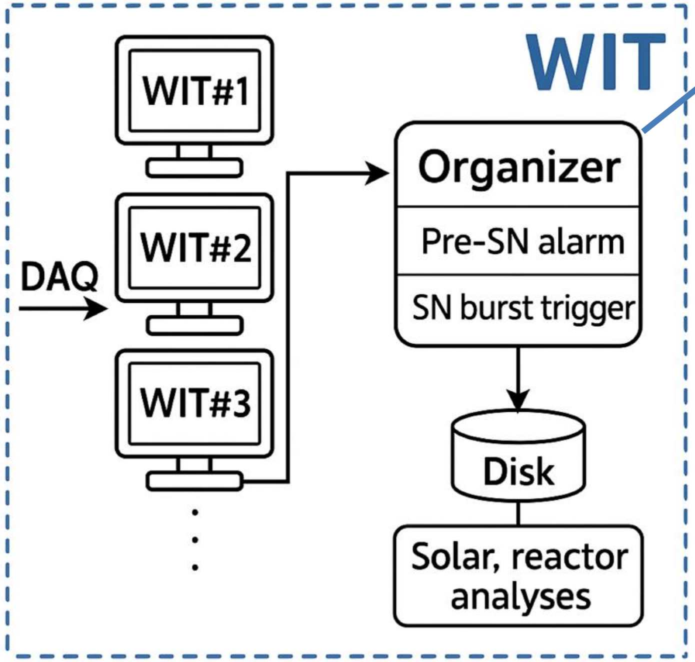


Diagram by Y. Hayato
Modified by Ll. Marti

The Wideband Intelligent Trigger (2)

WIT is a computing farm running in parallel to other SuperK triggers.

- 17 machines processing data in parallel + one organizer.
- ~850 hyper-threaded cores dedicated to real-time data processing.
- Each core handles blocks of 23 ms data files sequentially, applying a set of criteria to select good-quality events.
- Floating threshold of 11 hits above dark noise rate.



Organizes reconstructed events that arrive time-unordered. Data files grouped into segments lasting about 1.5 minutes each.

WIT also hosts:

- Pre-supernova alarm:
  SK-only and SK+KamLAND
- SN burst trigger
- SN-triggered raw data saving system
- Gravitational-wave follow up trigger (in development)

WIT – Trigger Efficiency

Using calibration data from Ni/Cf source at different positions in the SK detector (Z= +12, 0, -12).

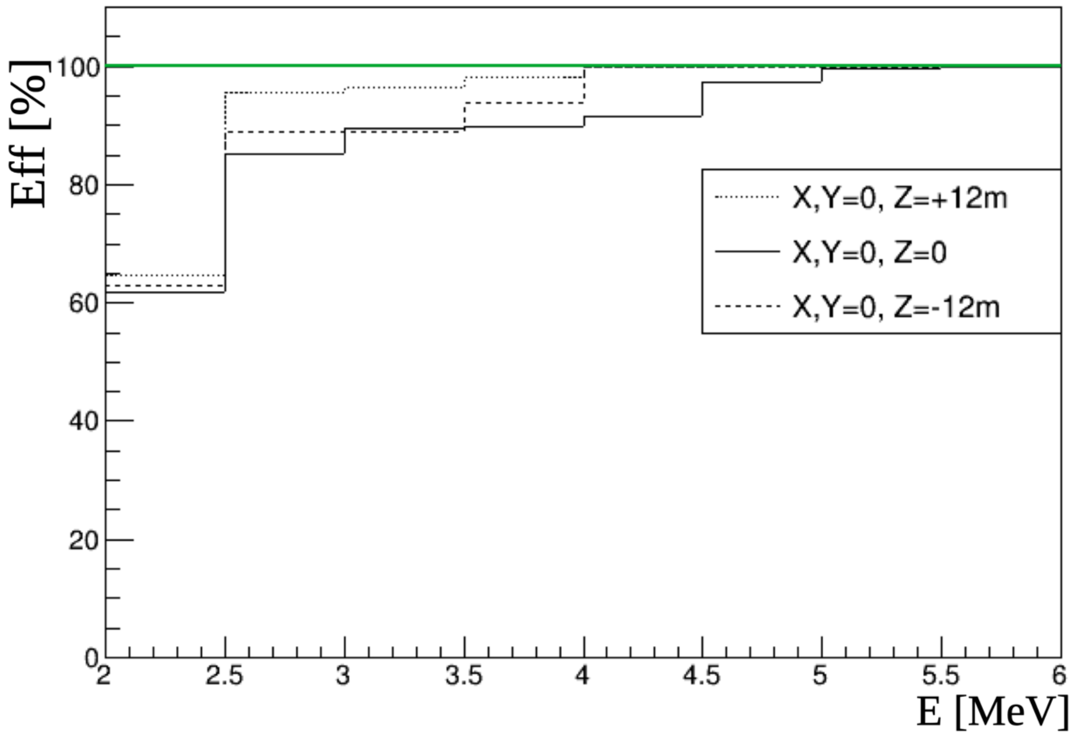
Two different methods compared:

- Time of Flight (ToF) method: ≥ 8 hits above background in 20 ns with ToF consistent with source → reconstructed vertex.
- Standard (STD) WIT chain: ≥ 11 hits above background in 230 ns over background → usual reconstruction (+ standard cuts).

$$\varepsilon = \frac{S_{STD} - \lambda_1 B_{STD}}{S_{ToF} - \lambda_2 B_{ToF}}$$

Stable performance across source positions (Z = +12, 0, −12 m).

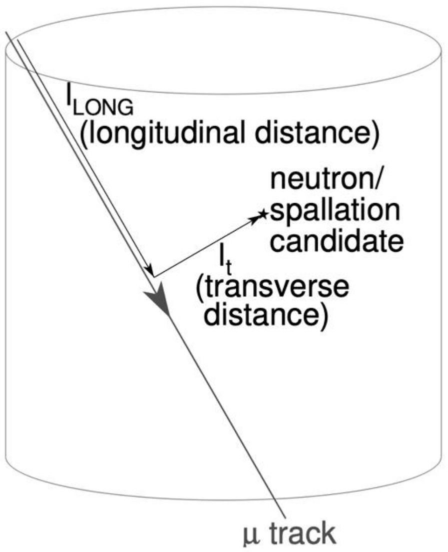
WIT trigger efficiency:



WIT delivers high efficiency at few-MeV energies

Spallation Reduction

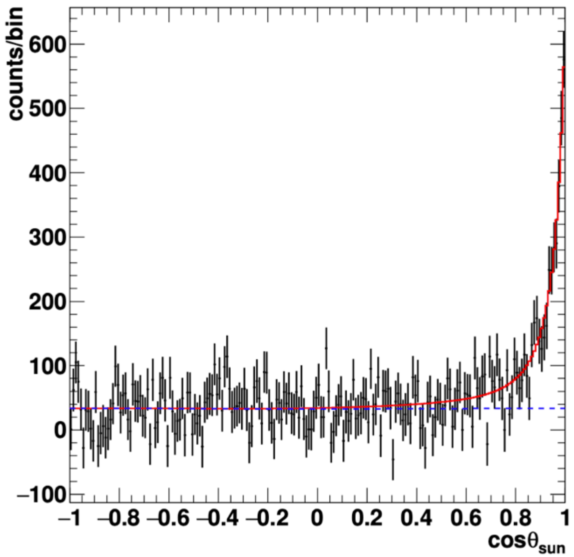
Find muon-induced hadronic showers by tagging neutron clouds (2.2 MeV γ from n-H capture) using WIT data
Using space–time correlations + likelihood cuts; validate with a new FLUKA-based spallation simulation.
Crucial to reduce backgrounds for solar neutrino analysis.



Main target: ^{16}N (from (n,p) interactions on ^{16}O): 7.3s half-life, several meters from muon track.

Muon → Shower → n-captures → WIT tag → Likelihood cut.

- Reconstruct neutron clouds from many 2.2 MeV γ-tags after a muon.
- Cut on transverse (l_t) and longitudinal (l_{LONG}) distances to the cloud → isolate spallation decays from true low-E events.
- Preselection + likelihood cuts (~90% spallation cut at high signal efficiency).



Impact on SK-IV solar analysis:

New cuts using neutron-cloud info reduce deadtime by up to ~55%.

+12.6% solar signal efficiency for 2790 × 22.5 kton·day exposure (equivalent to one extra year).

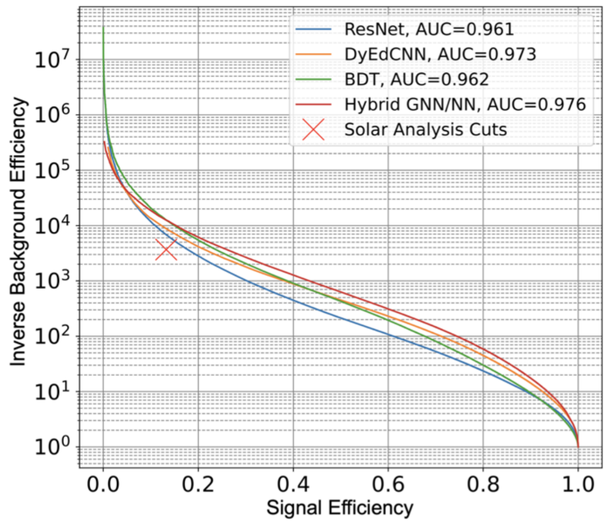
This framework opens lower-energy windows and strengthens solar and other low energy analyses, especially with SK-Gd.

New Methods and Simulations for Cosmogenic Induced Spallation Removal in Super-Kamiokande-IV - Phys. Rev. D **110**, 032003 (2024)

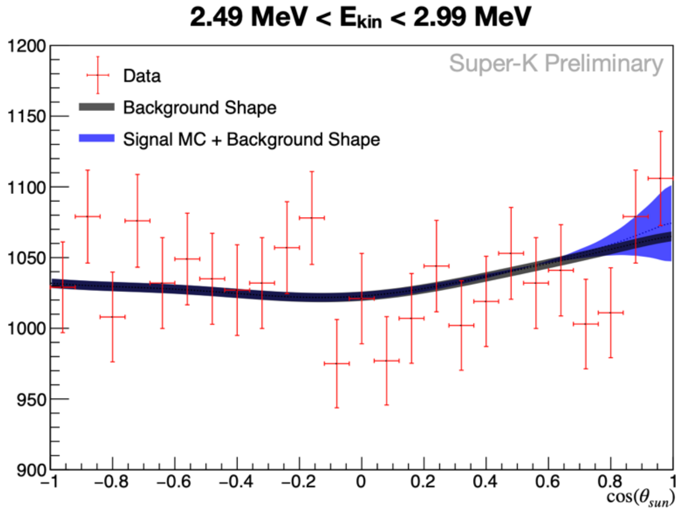
Solar Analysis with WIT

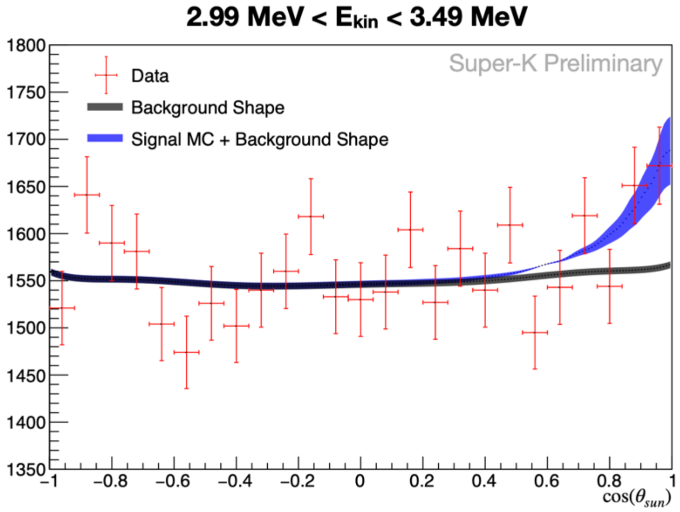
Lower the energy threshold of the SK-IV solar analysis, using boosted decision trees (BDT) in WIT data, aiming to observe upturn in the electron neutrino survival upturn (vacuum > MSW).

- WIT data available for 618 days of SK-IV;
- Many advanced machine learning methods compared, with BDT offering high background rejection;
- Analysis of the solar neutrino flux at E_{kin} < 3.49 MeV.



Observed/Expected = $\begin{cases} 0.11^{+0.37}_{-0.36}, \text{ for } E_{kin} \text{ 2.49–2.99 MeV} \\ 0.425^{+0.148}_{-0.064}, \text{ for } E_{kin} \text{ 2.99–3.49 MeV -> } \underline{\mathbf{2.66\sigma}} \end{cases}$

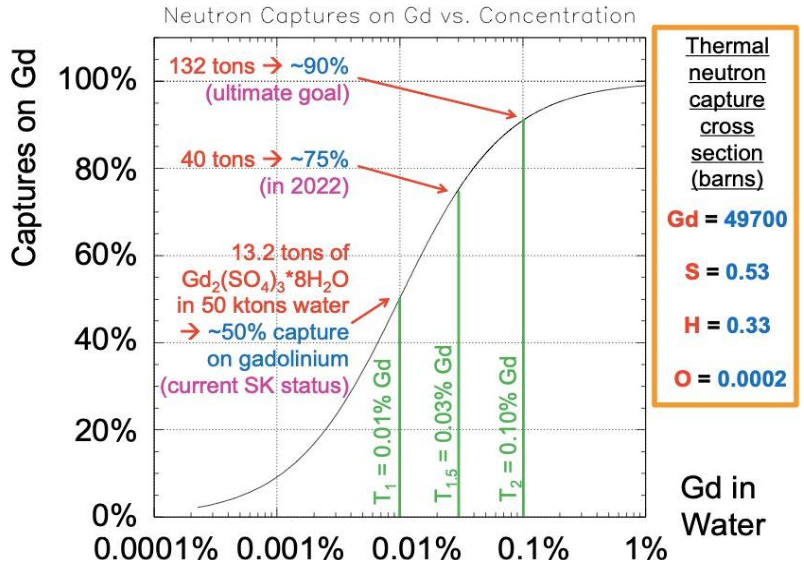




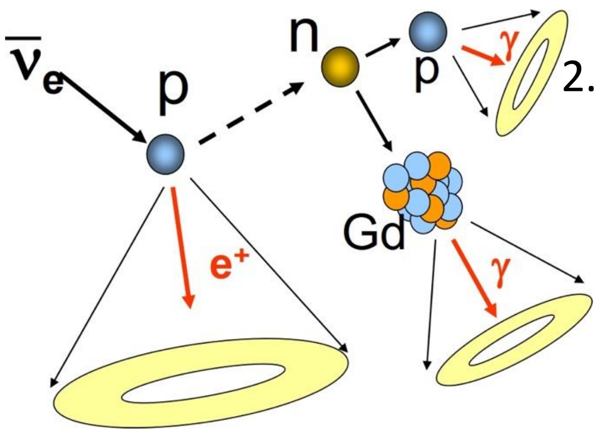
Background levels remain too high to have a meaningful effect on the study of the solar upturn.

Super-Kamiokande with Gadolinium

+



Enhance sensitivity to low energy electron anti-neutrinos!



ΔT ~200 μs

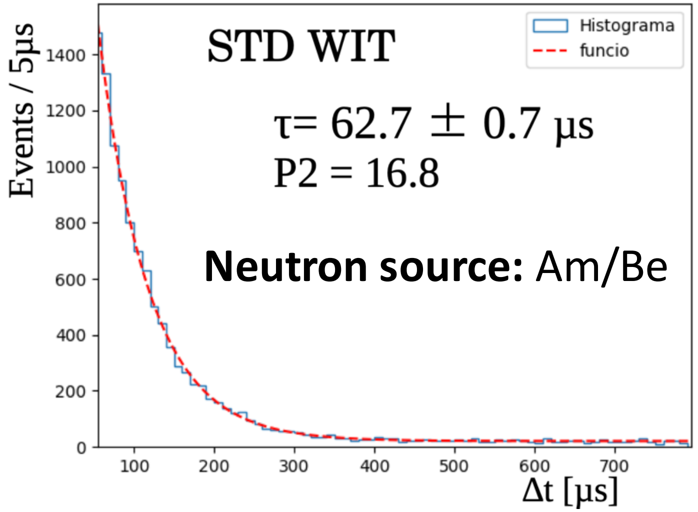
$\Delta T_{0.03\%\ Gd}$ ~60 μs

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

Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166248

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

Nuclear Inst. and Methods in Physics Research, A 1065 (2024) 169480



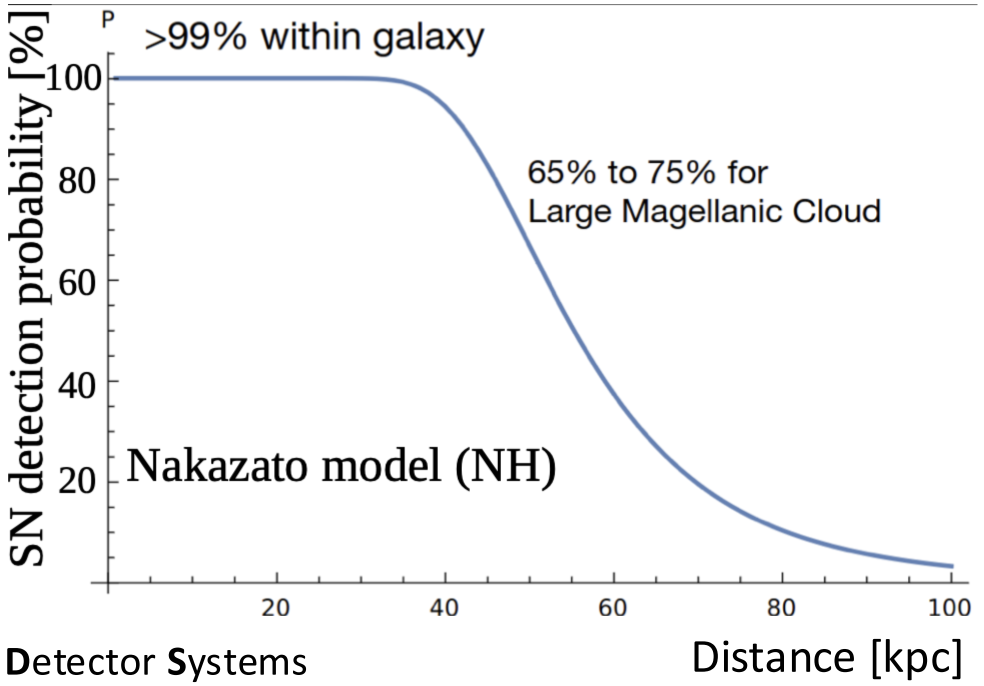
Neutron source: Am/Be

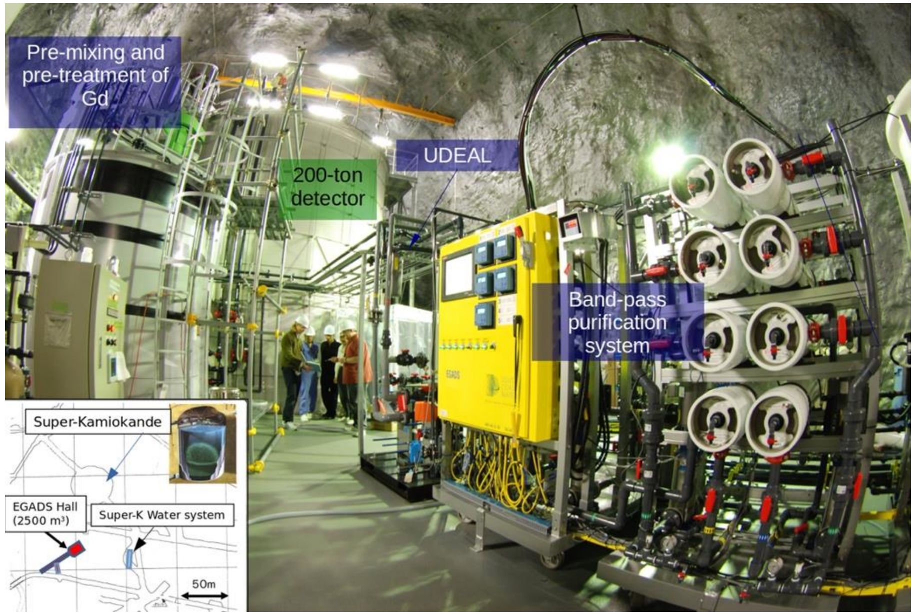
WIT online SN alarm

Scans for IBD candidates in 10 second windows.
- If >10 candidates are found, a SN alarm is issued.
- Raw data buffer: last ~5 min continuously kept and saved on alarm.

WIT can handle all SN-related data and issue SN alert in ≤ 22 s, even for a nearby SN (LED burst tests).

Future improvements:
- Deliver in ~40 s: event count, energy spectrum, and SN direction;
- Machine learning-based methods for SN direction estimation.





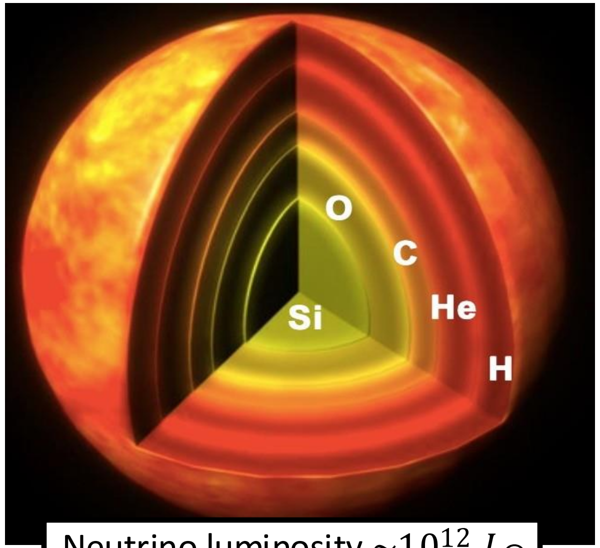
EGADS:
Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems
Test facility for SK-Gd, standalone detector.

HEIMDALL: **H**igh **E**fficiency **I**BD **M**onitoring **D**etector and **A**utomated ca**LL**
can issue an alert even if SuperK is on Test/Calibration run or down!

https://www-sk.icrr.u-tokyo.ac.jp/egadsSNalarm/

For automated emails: martillu@suketto.icrr.u-tokyo.ac.jp

Pre-Supernova (Si-burning) Stars



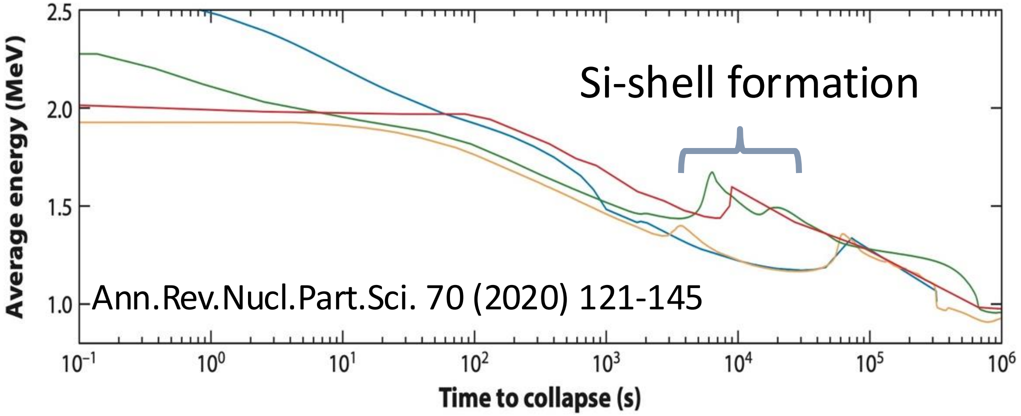
Neutrino luminosity $\sim 10^{12}\ L_{\odot}$
Photon luminosity $\sim 10^{5}\ L_{\odot}$

Massive-star life cycle (M $\gtrsim$ 8 $M_{\odot}$):
Main sequence: Hydrogen → Helium in core.
Helium → Carbon/Oxygen (core He burning). Shell burning ignites!

Progressively heavier nuclear burning as core temperature and density rise.
Carbon burning → Ne, Na, Mg (~10^3 yr)
Neon burning (~1 yr)
Oxygen burning (months → weeks)
Silicon burning (days → hours) → builds iron core → core collapse supernova (CCSN)

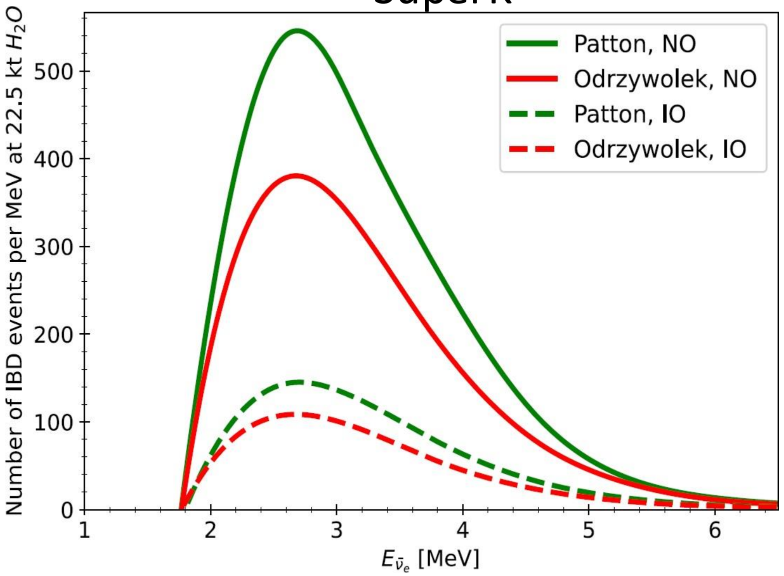
Neutrino emission increases (cooling).

Neutrino-cooling star or pre-supernova (preSN) star

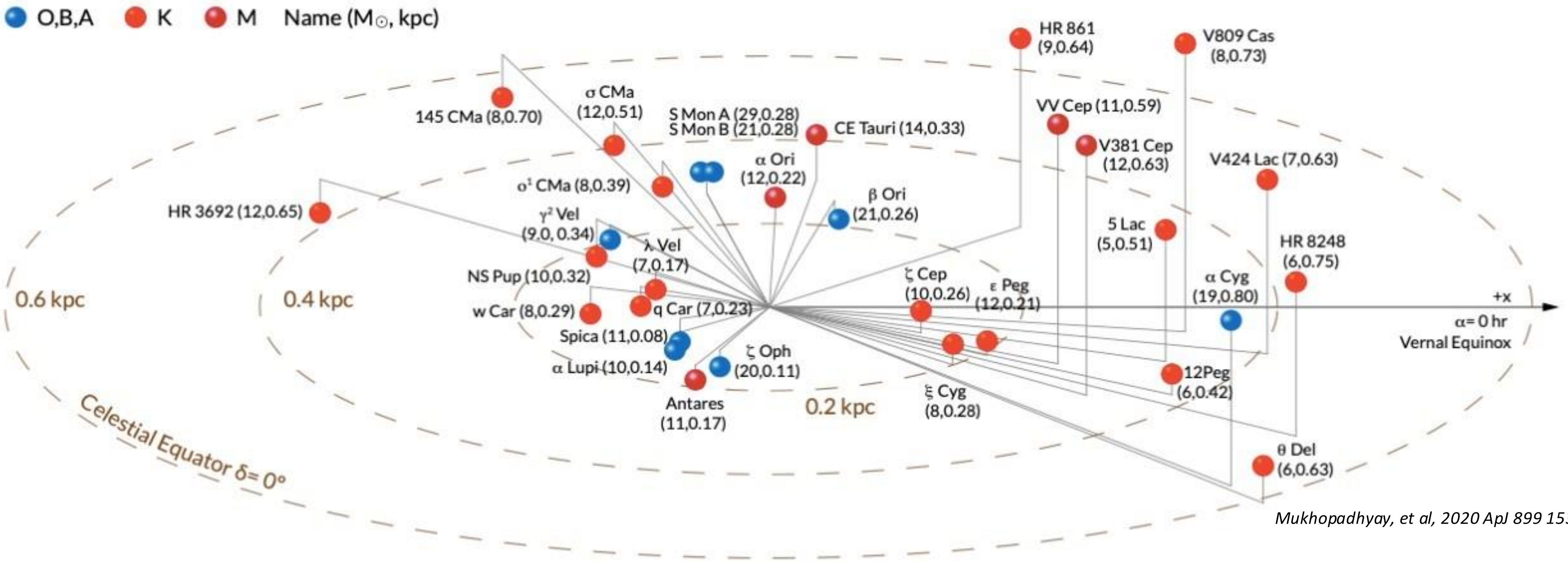


Neutrino production:

- Mainly from electron-positron annihilation
- Nuclear weak processes (close to core-collapse)
- $\bar{\nu}_e$ in the few-MeV range → **IBD interactions in SK-Gd**



Pre-Supernova Neutrinos in SK-Gd



Mukhopadhyay, et al, 2020 ApJ 899 153

- 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.**

Sensitivity to pre-supernova neutrinos

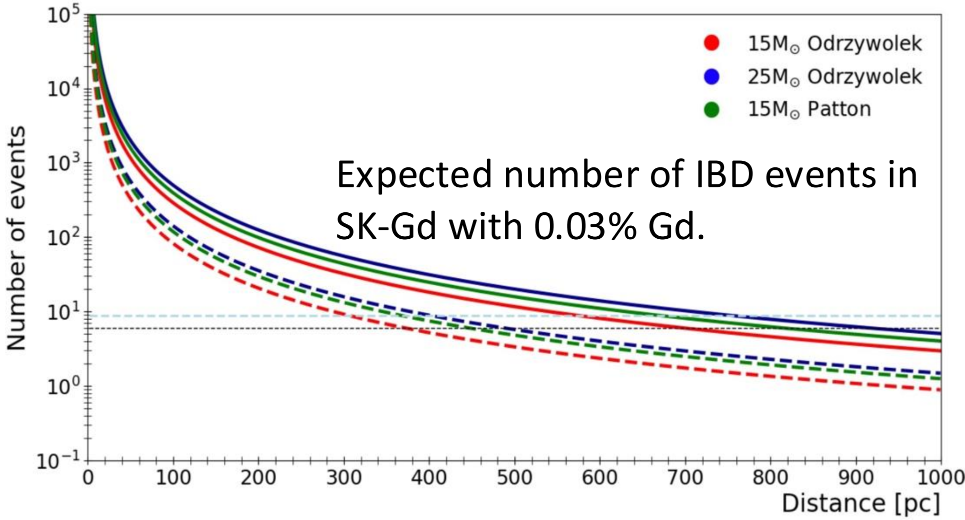
Sensitivity estimation in SK-Gd: L. N. Machado *et al* 2022 *ApJ* 935 40

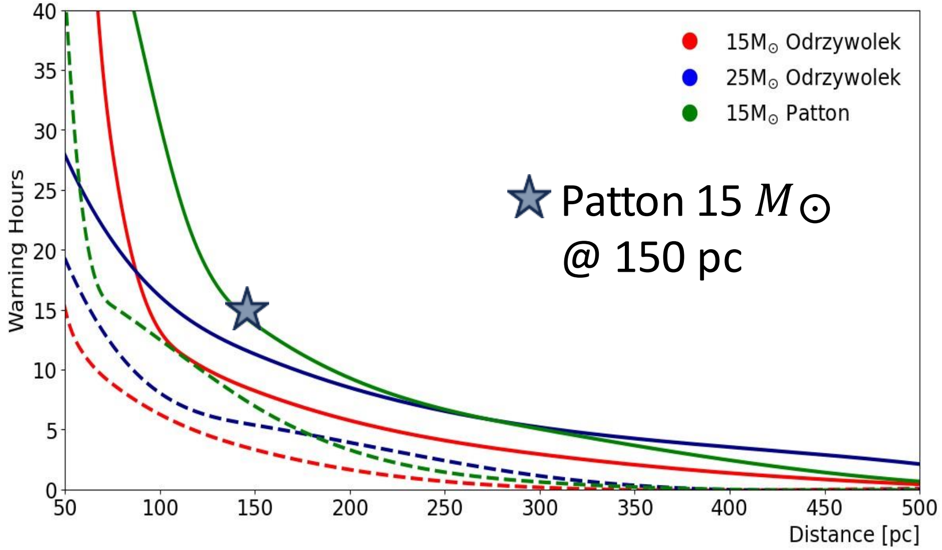
Selection of IBD pairs: Based on temporal/spacial correlation of IBD products and boosted decision tree.

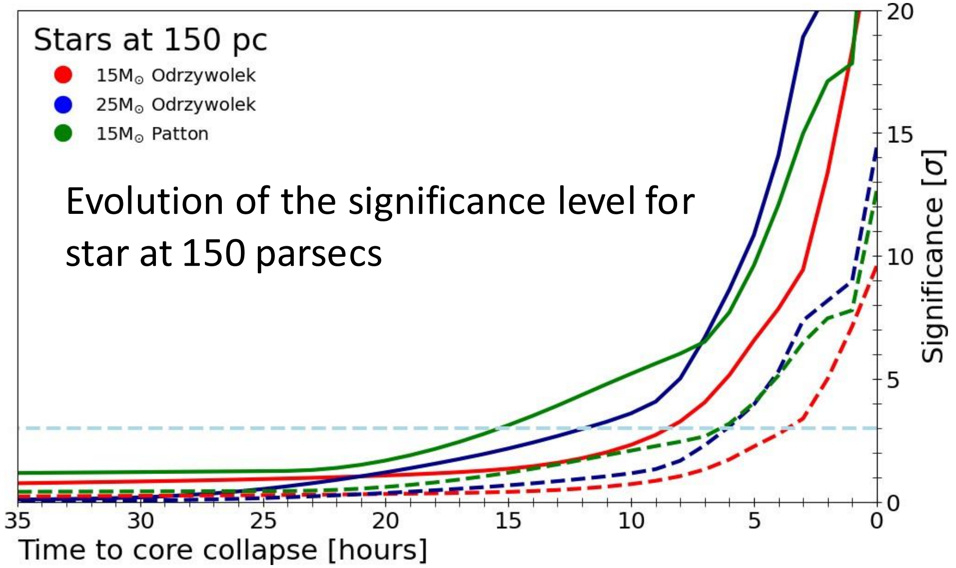
Models considered: **Odrzywolek**, et al 2010 Acta Phys. Pol. B 41, 1611 and **Patton**, et al 2017 ApJ 851 6.

Background: reactor neutrinos, geoneutrinos, spallation, accidental coincidences.

Early warning system for supernovae based on the search for preSN $\bar{\nu}_e$ running in WIT since **October 2021** → Data is received immediately after fast online reconstruction.

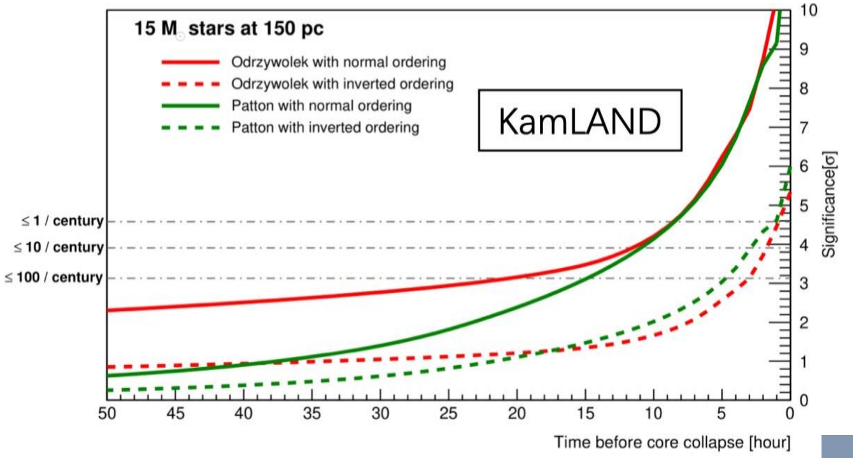


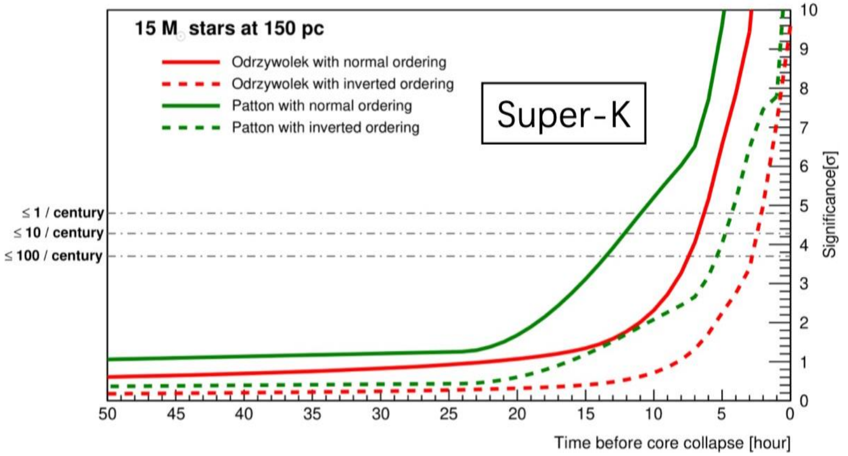




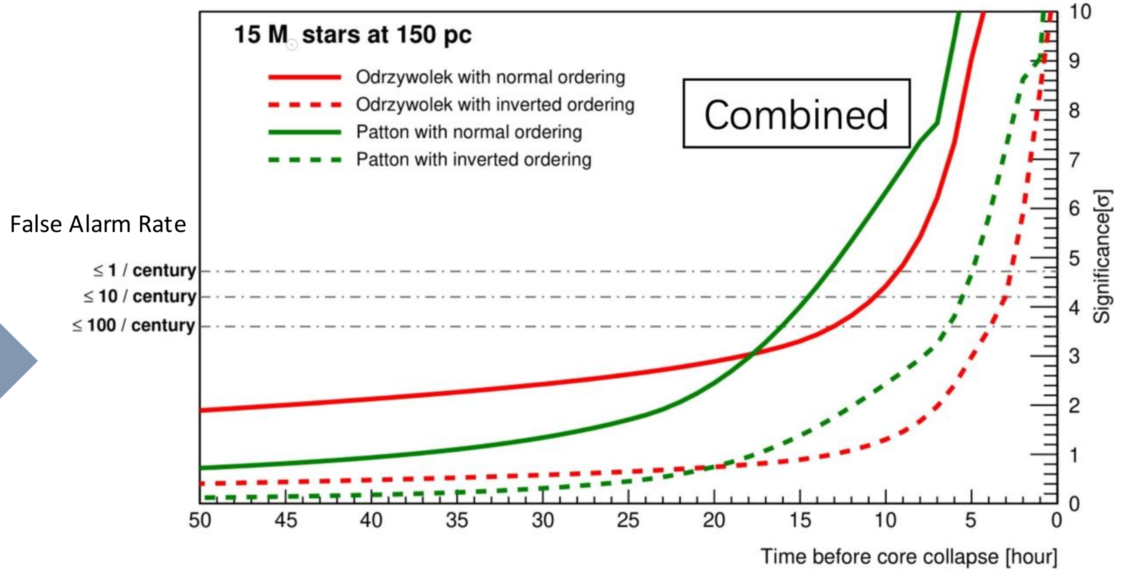
Combined SK and KamLAND preSN Alarm

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





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



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.

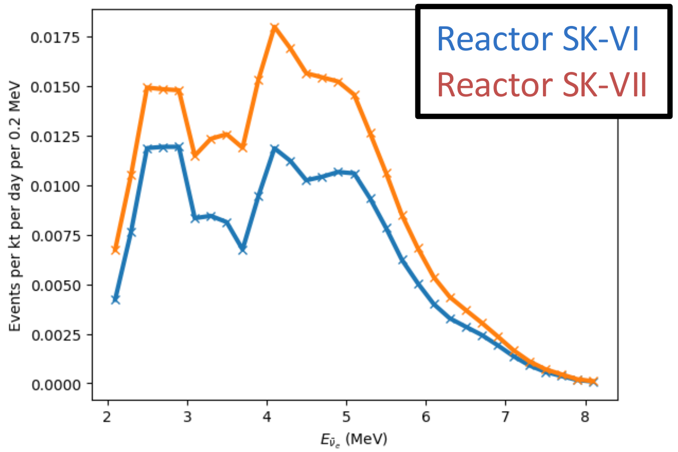
System is open to public:
https://www.lowbg.org/presnalarm/

See talk “Development of early warning method using pre-supernova neutrino light curves” – K. Saito (Thursday)

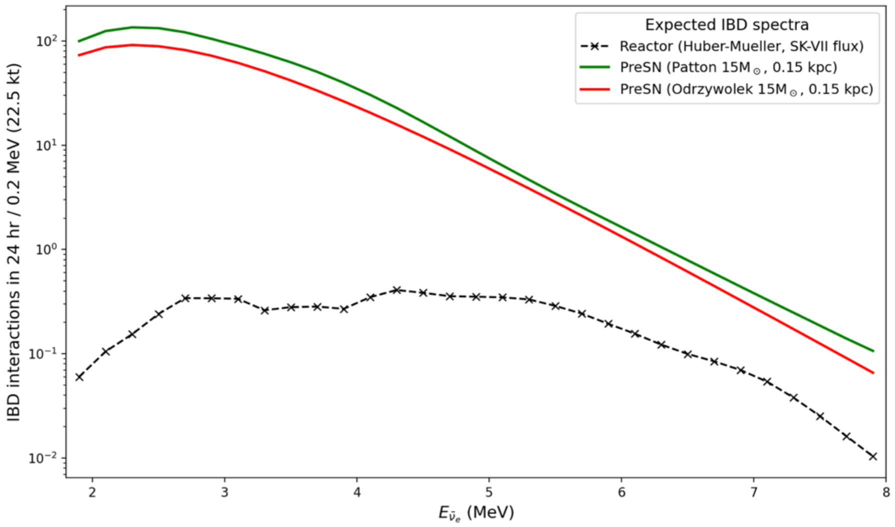
Reactor Neutrinos

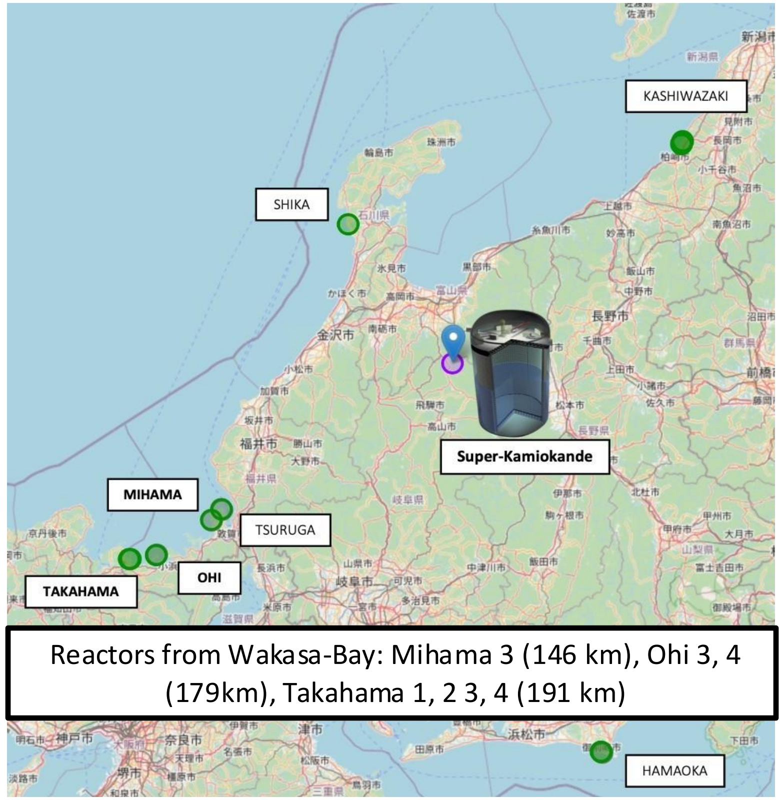
The efficient neutron identification provided by gadolinium allows the search for signals from nuclear power reactors (electron anti-neutrinos from fission products).

Reactor neutrinos are in the same energy region as preSN neutrinos.



Expected reactor events in SK (model Huber/Muller)





Reactors from Wakasa-Bay: Mihama 3 (146 km), Ohi 3, 4 (179km), Takahama 1, 2 3, 4 (191 km)

Same analysis strategy applied to search for reactor $\bar{\nu}_e$

Reactor fluxes in SuperK are primarily a result of the activity of Japanese nuclear power reactors (small contribution from Korean reactors).

Expected ~ 5 events/day.

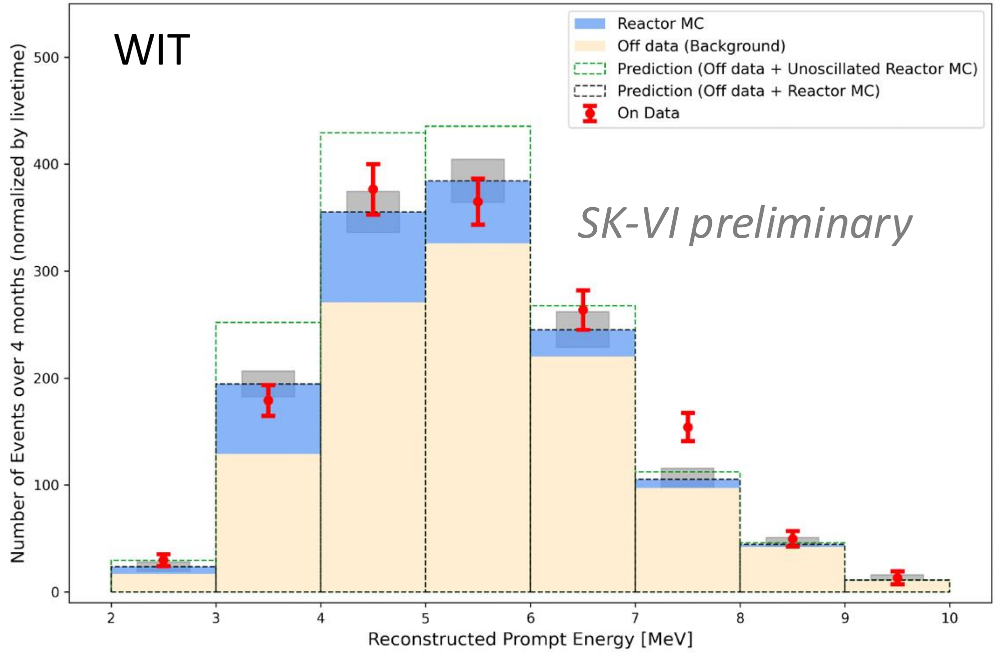
- Main backgrounds: accidental coincidences, spallation.
- Detection in SuperK would be one of the first in water Cherenkov detectors!
- Help in constraining further neutrino oscillation parameters ($\sin^2\theta_{12}$, Δm^2_{21})

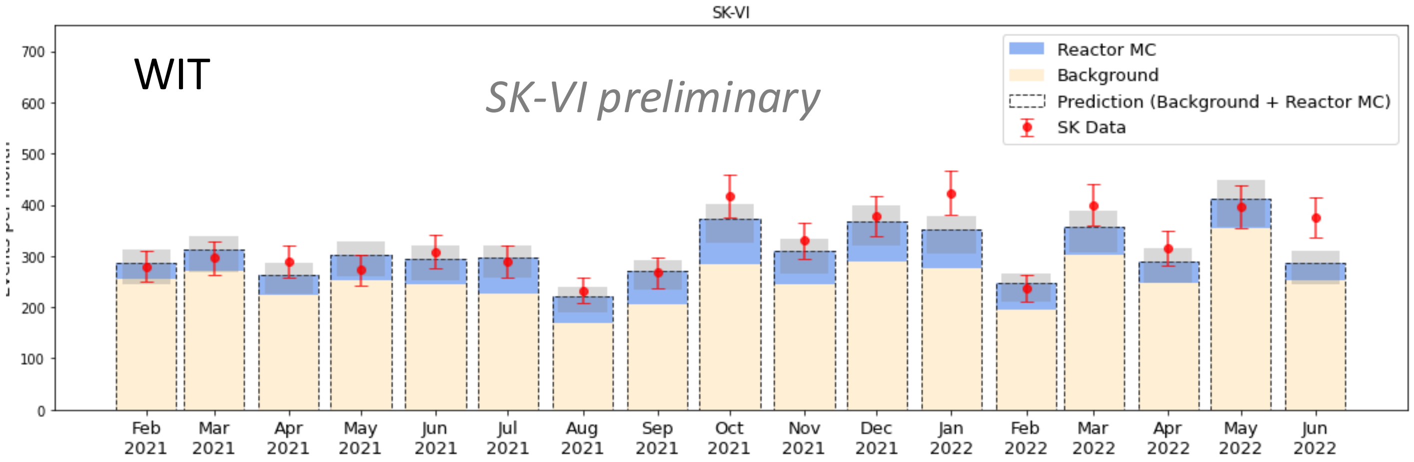
Reactor Neutrinos

Two analyses are currently being carried out using two different low energy triggers (SLE and WIT).

- On and off analysis (similar to KamLAND strategy) perfomed: SK-VI (0.01% Gd) had two clear ”on” and ”off” reactor activity periods for nuclear power plants near Super-K (each one ~4 months)
- Full analysis of both SK-VI and SK-VII data also carried out, comparing the observed data to estimations based on background modeling and reactor Monte Carlo simulations.

ON/OFF analysis



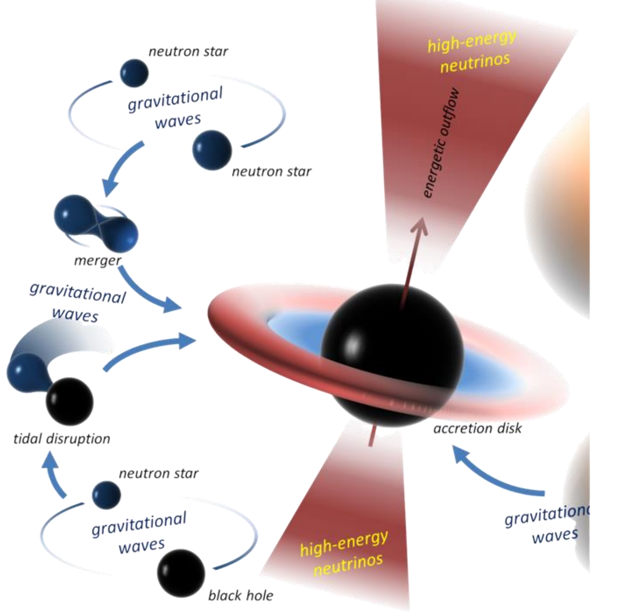


Currently validating both analyses and papers in preparation!

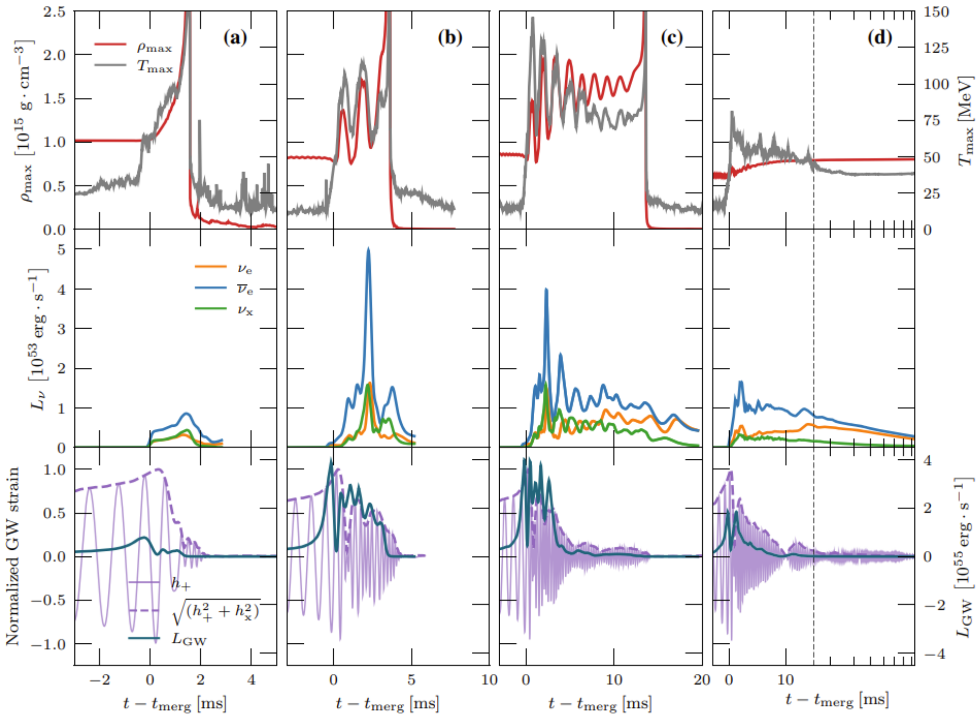
Gravitational Wave Follow-up in WIT

Compact binary mergers are prime candidates for neutrino–gravitational wave coincidence searches:

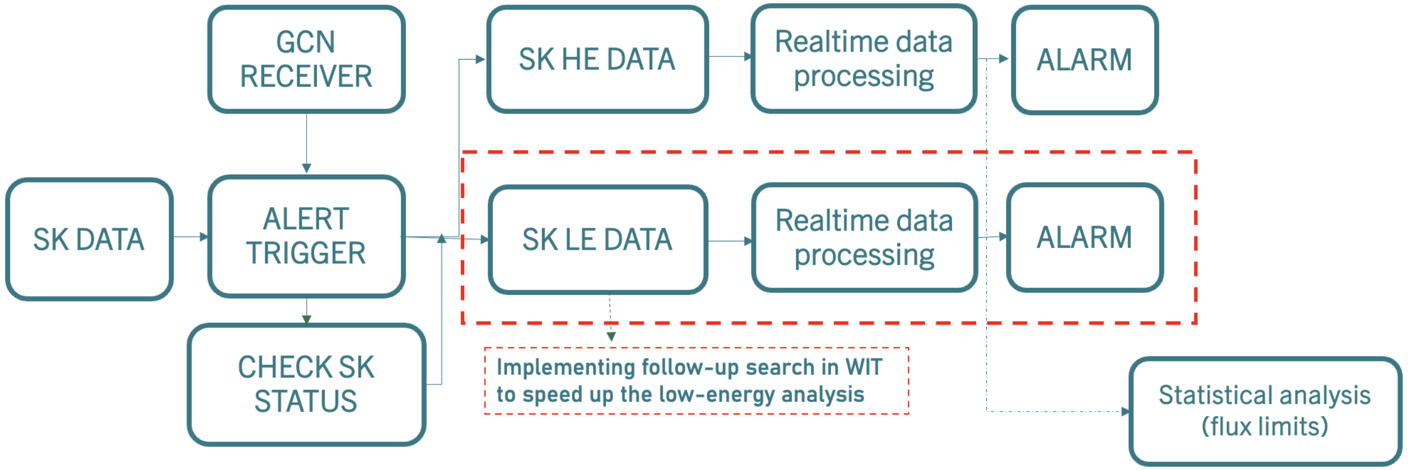
- **Neutron Star–Black Hole (NSBH) mergers:**
  may produce both high-energy and thermal neutrinos, depending on remnant and ejecta.
- **Binary Neutron Star (BNS) mergers:**
  emit low-energy neutrinos (MeV) within milliseconds of the GW signal.



Models expect that BNS and NSBH mergers emit thermal MeV neutrinos within < 1 s of merger, with peak luminosity > 10^{53} erg/s, in the 5 to 30 MeV range. Higher luminosity: $\bar{\nu}_e$.



Look for coincidences in SuperK in both low- and high- energy samples. Currently implementing real-time system in WIT:



Summary

The Wideband Intelligent Trigger (WIT): is a software trigger with online reconstruction running in parallel to standard triggers. The WIT system is a computing farm with 20 machines (19 processing data in parallel + one organizer) and ∼900 hyper-threaded cores.
WIT pushes traditional triggers hit threshold down to reach < 4 MeV causes huge fake rates from dark noise + radioactivity.

Spallation reduction

- Aimed to suppress long-lived isotopes (e.g., ^{16}N).
- Reconstruct neutron clouds from many 2.2 MeV γ-tags after a muon
- Cuts save deadtime and keep signal efficiency.

Solar analysis

- Higher low-E efficiency (sub-4 MeV window) + BDTs on WIT data.
- Aiming to observe upturn in the electron neutrino survival upturn.
- 2.66σ evidence for a solar signal in WIT.

Supernova online monitor

- Searches IBD candidates in 10 second windows; alarm if >10 found.
- Improvements on-going: deliver in 40 seconds: event count, spectrum, improved direction fitter using machine-learning.

Pre-supernova (pre-SN)

- Sensitivity to few-MeV electron antineutrino from late burning (Si) hours–days before collapse.
- Potential early-warning channel for nearby massive stars.

Reactor neutrinos

- Low-E capability + n-tagging improves reactor neutrino search.
- Based on preSN selection.
- ON/OFF and full data analyses conducted.
- Currently validating and paper in preparation.

GW follow-up

- Rapid, low-threshold pipeline supports gravitational-wave alerts: prompt low-E neutrino searches.