Applied Antineutrino Physics (AAP) Workshop
York, 18-23 September 2023

Reactor neutrinos in Super-Kamiokande with Gadolinium

September 20th, 2023

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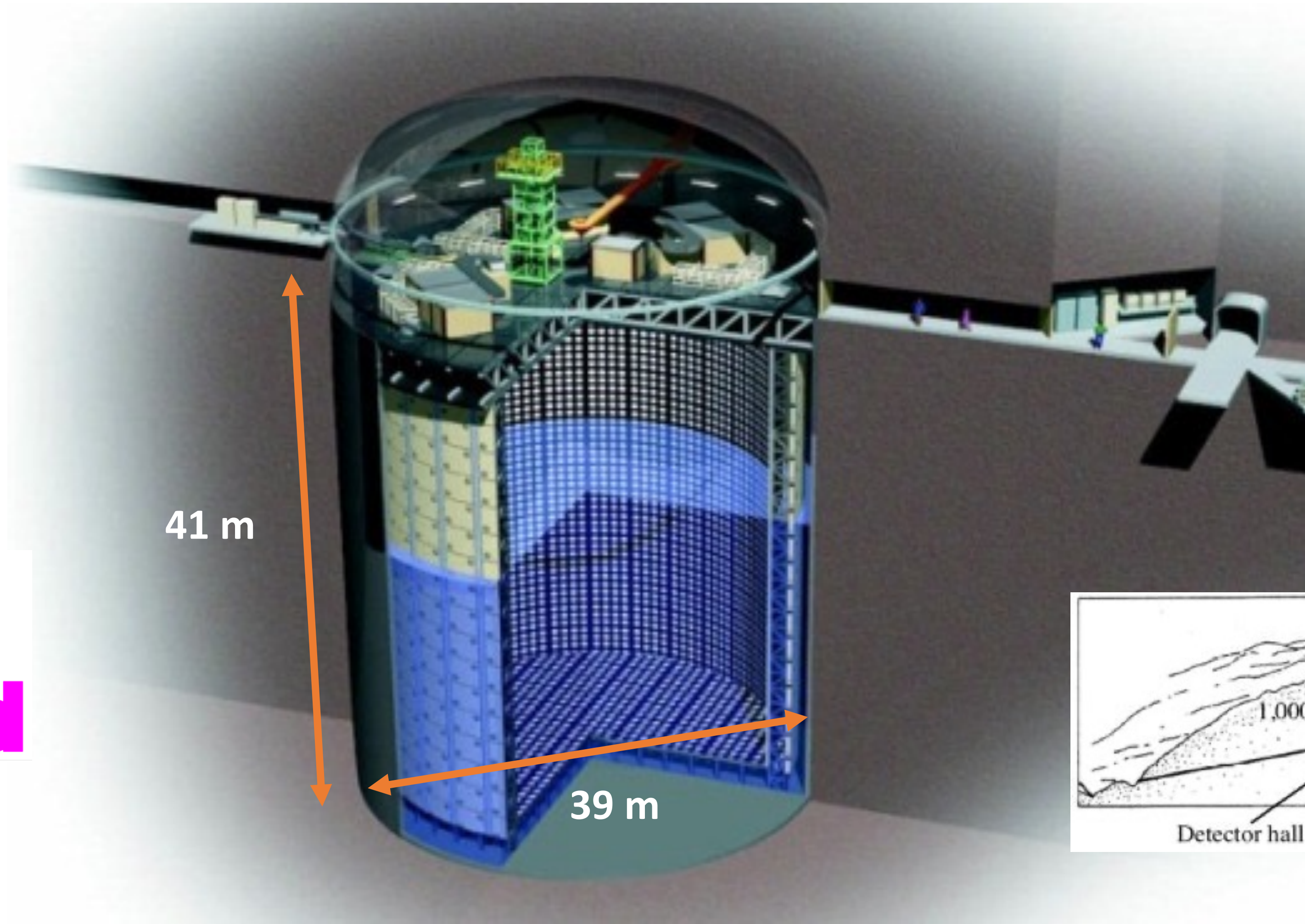
The Super-Kamiokande Experiment

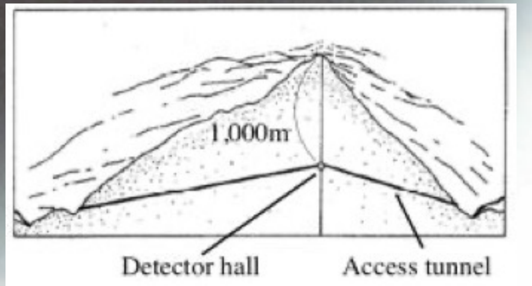
The Super-Kamiokande (SK) Detector is a neutrino observatory located in the Kamioka mine in Japan.
50 ktons water Cherenkov detector – 22.5 ktons fiducial volume.

2020



Inner detector: ~11,000 20-inch PhotoMultipliers Tubes (PMTs).

Outer detector: 2m thick, ~1,885 8-inch PMTs.



The Super-Kamiokande Collaboration

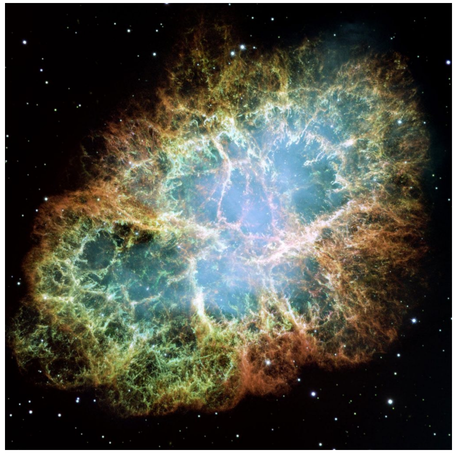
The Super-Kamiokande Collaboration consists of 236 members from 54 institutions.

Photo taken in the last collaboration meeting – May 2023

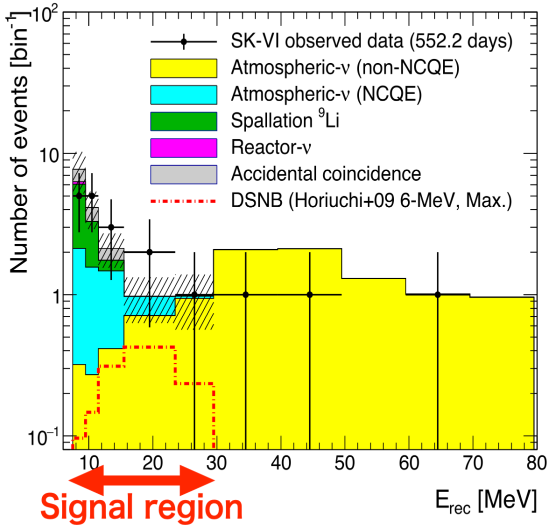
Super-Kamiokande – Physics Goals

Super-Kamiokande is a multi-purpose observatory:

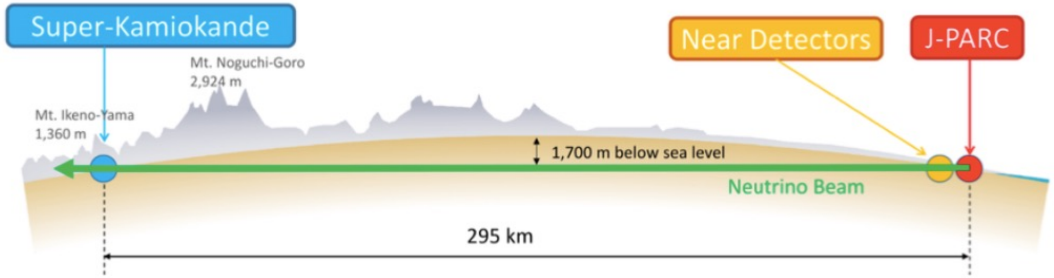
- Solar neutrinos;
- Atmospheric Neutrinos;
- Accelerator (T2K);
- Supernova burst neutrinos;
- Nucleon decay;
- Indirect search for DM;

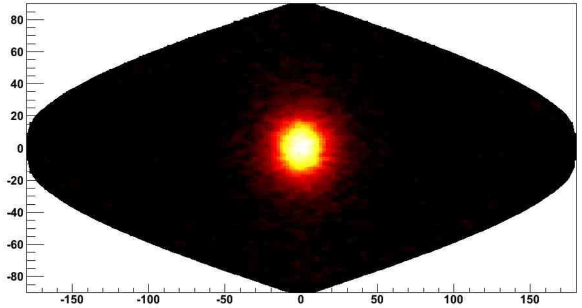


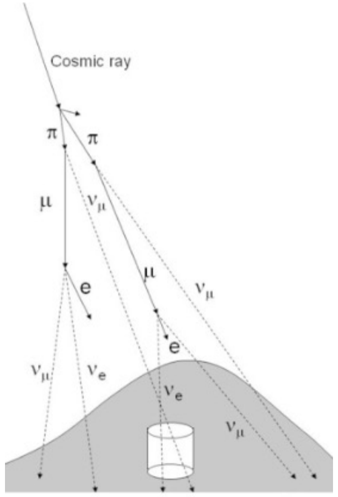
- **Diffuse Supernova Neutrino Background;**
- **Pre-Supernova;**
- **Reactor Neutrinos.**

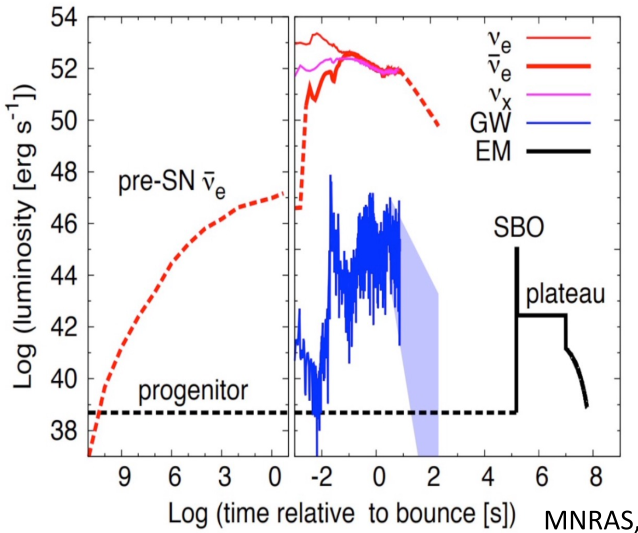


M. Harada et.al., ApJL. 951:L27 (2023)







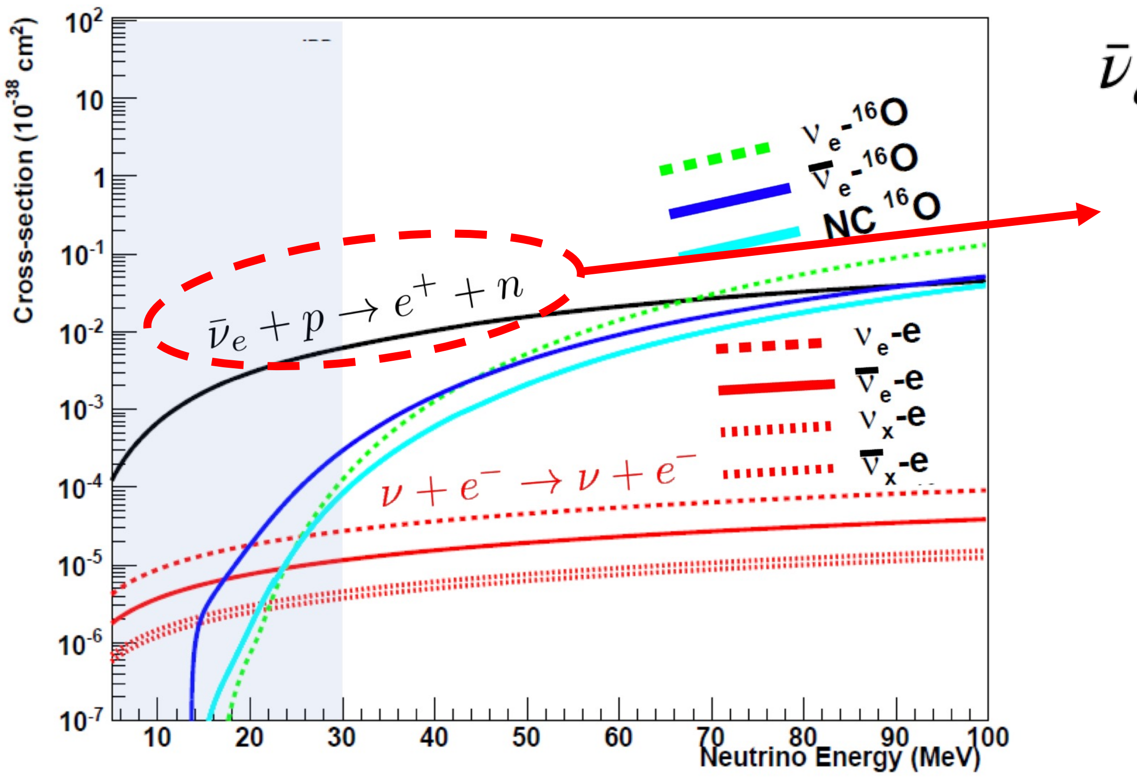


MNRAS, 461, 3296 (2016) arXiv:1602.03028

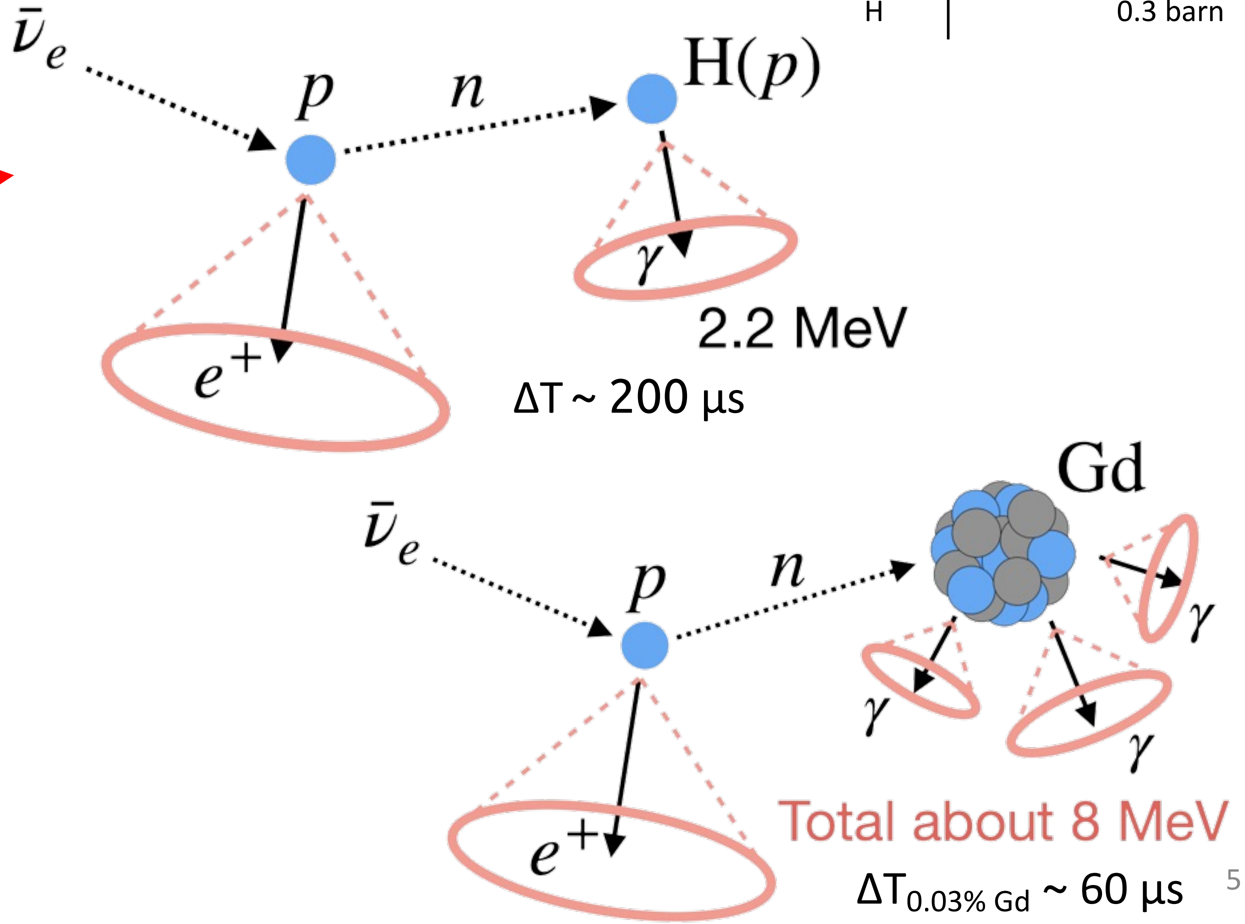
Super-Kamiokande with Gadolinium (SK-Gd)

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

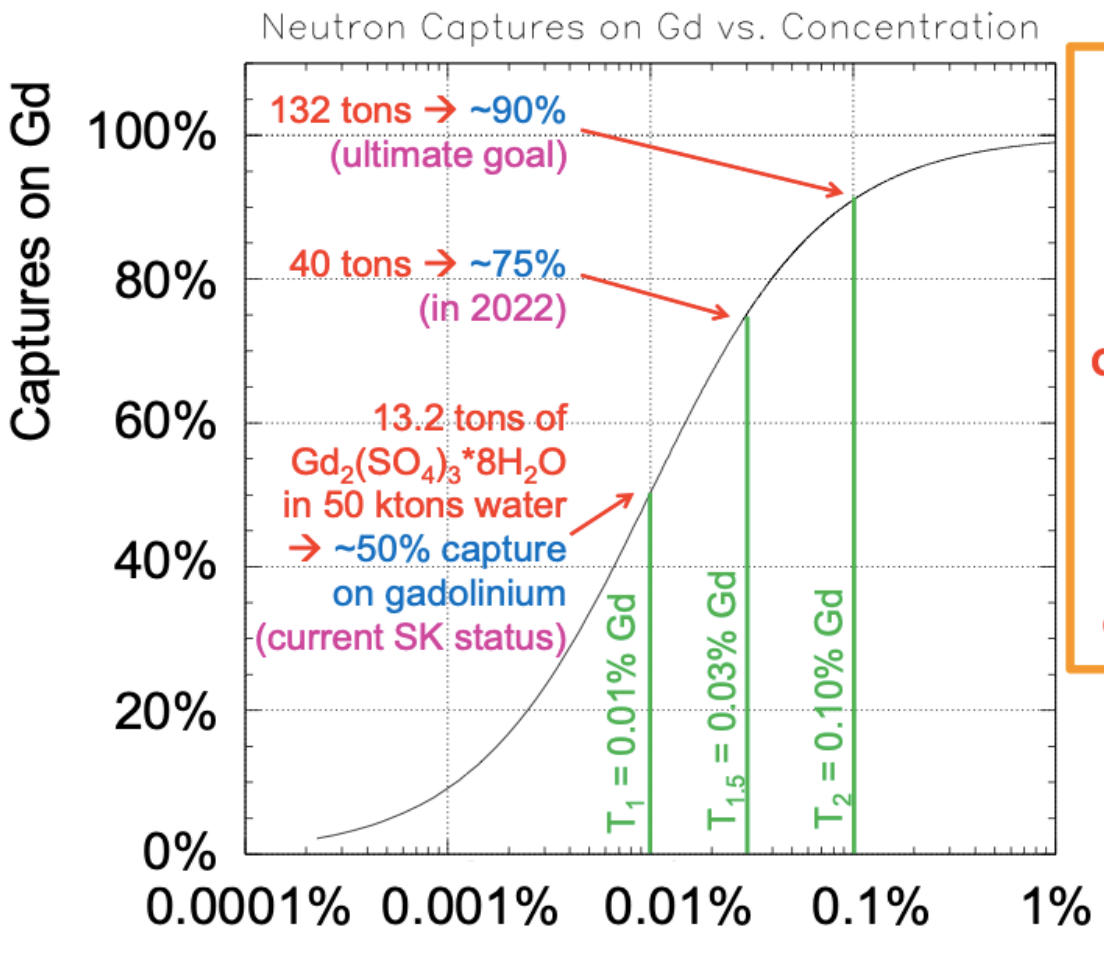


Relevant cross-sections in low energy.



Beacom, Vagins PRL.93, (2004) 171101

Super-Kamiokande with Gadolinium (SK-Gd)



Thermal neutron capture cross section (barns)

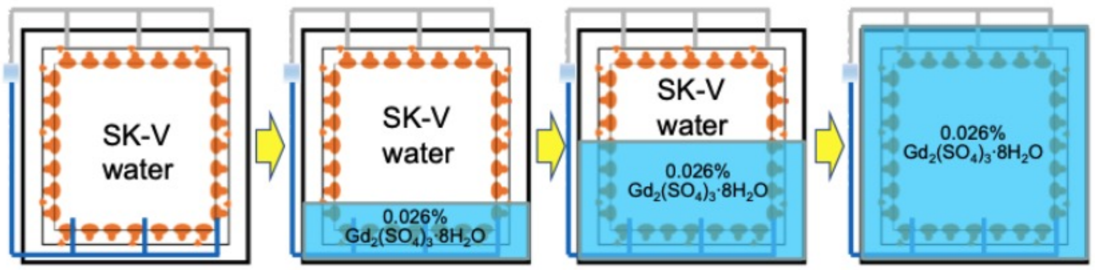
Gd = 49700

S = 0.53

H = 0.33

O = 0.0002

Gd in Water



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

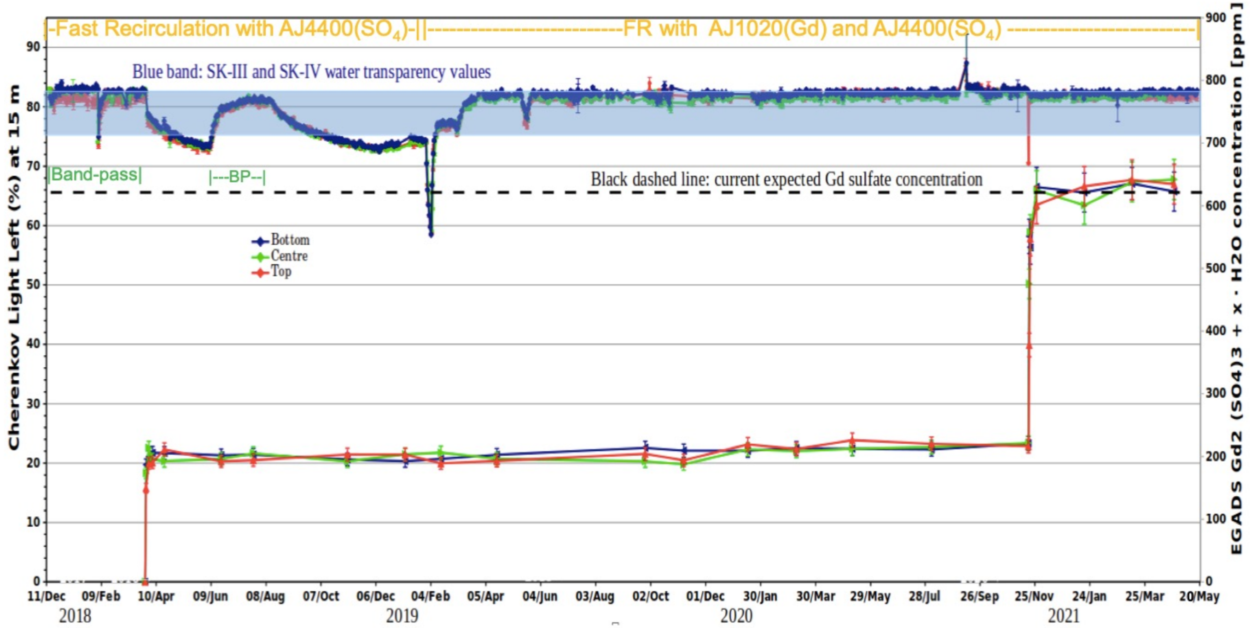
June/July 2022 → **40 tons $Gd_2(SO_4)_3$ * $8H_2O$**
<u>0.03% Gd (SK-VII)</u>

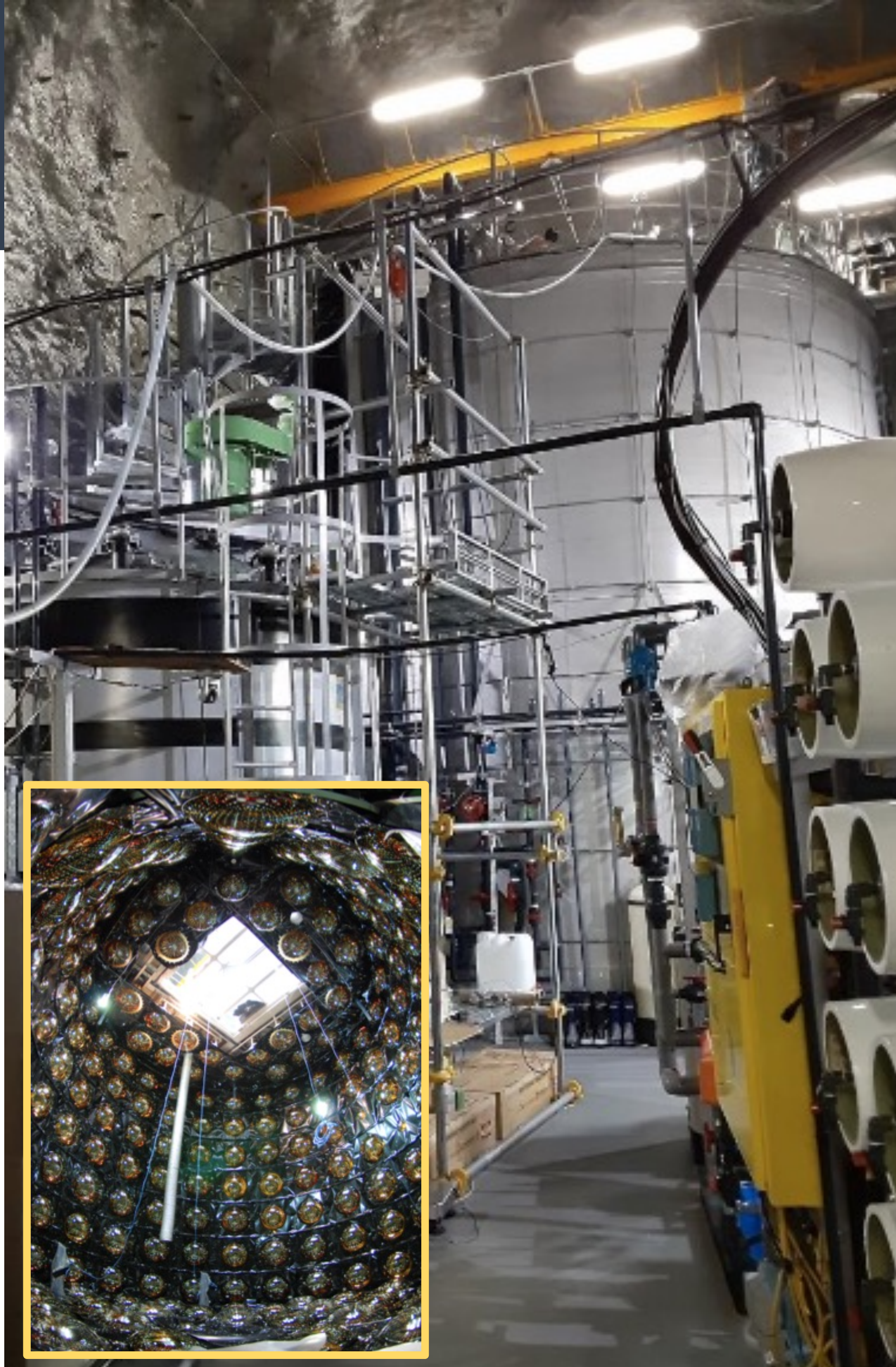
<u>Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166248</u>

Evaluating Gadolinium's Action on Detector System: EGADS

The EGADS detector has been used to simulate the gadolinium sulfate loading in Super-Kamiokande.

EGADS was designed to be a small prototype of SK-Gd, with only 200 tons of water, 227 PMTs installed and same electronics.





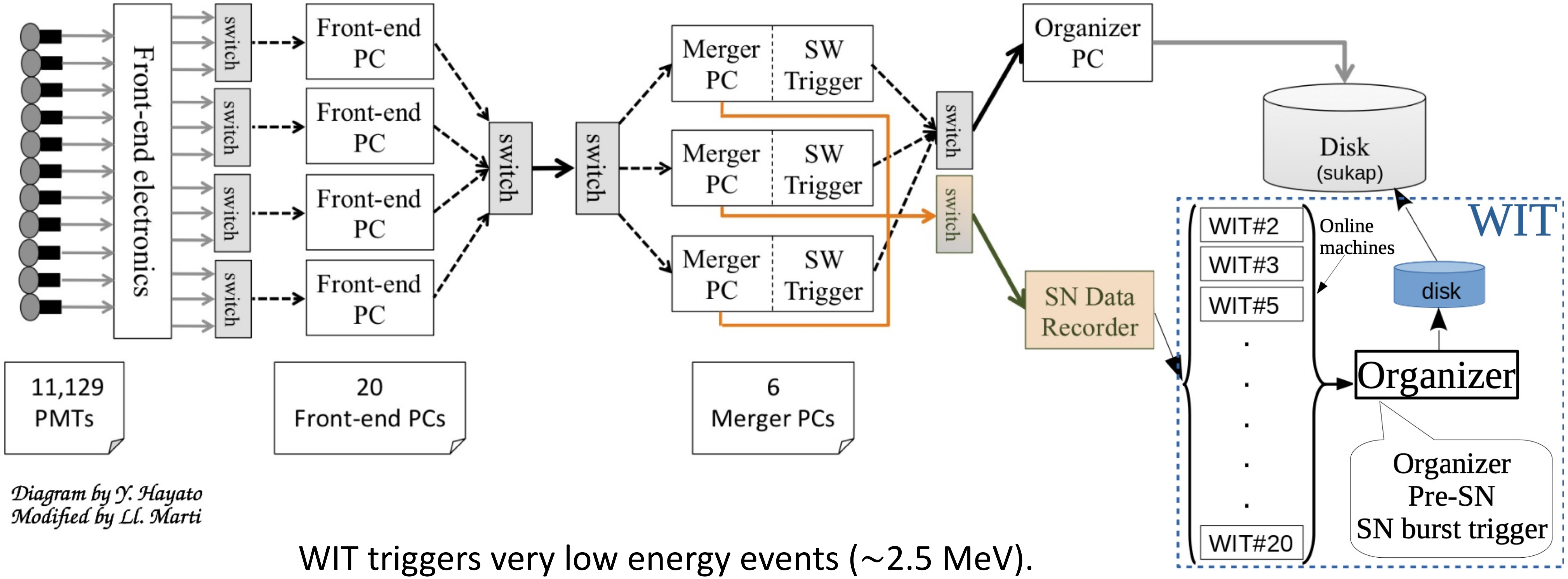
EGADS has also a standalone galactic Supernova monitor, called HEIMDALL (https://www-sk.icrr.u-tokyo.ac.jp/egadsSNalarm).

Ll. Marti et al, NIM A 959 (2020) 163549

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.

19 online machines (receiving 23ms data blocks) + 1 organizer (sorting blocks from online machines).



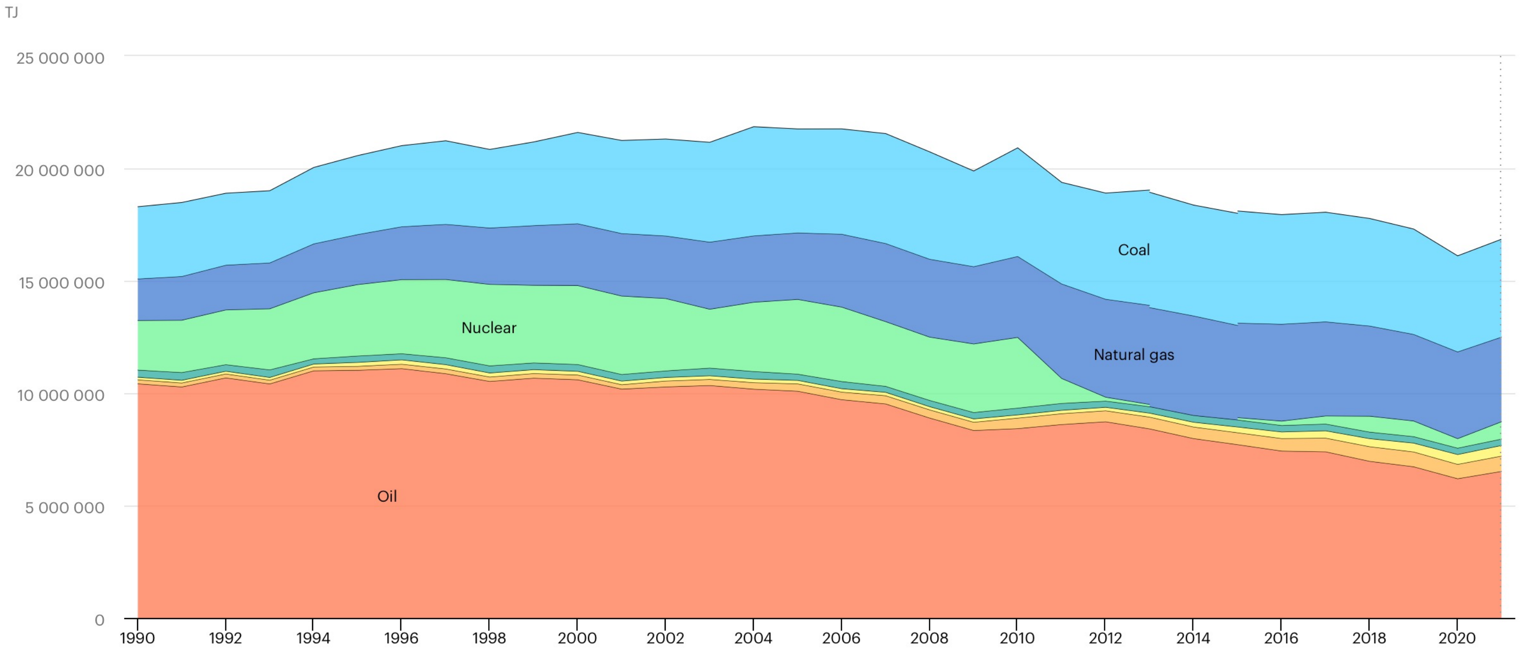
WIT triggers very low energy events (~2.5 MeV).

Japanese Nuclear Power Reactors

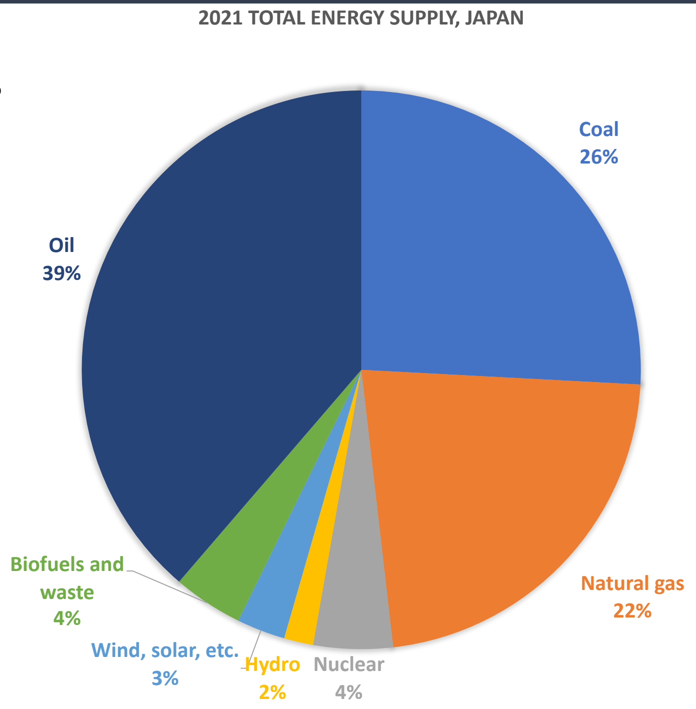
Japanese nuclear power reactors currently (2021) supplies approximately 4% of Japan's electricity. Up until 2011, 30% of electricity was from reactors.

Current plan: increase to 20% by 2030[1].

From [2]



Energy supply by source in Japan over the years. From [2].



As a result of the 2011 Fukushima Daiichi nuclear incident, all nuclear reactors were gradually shut down.

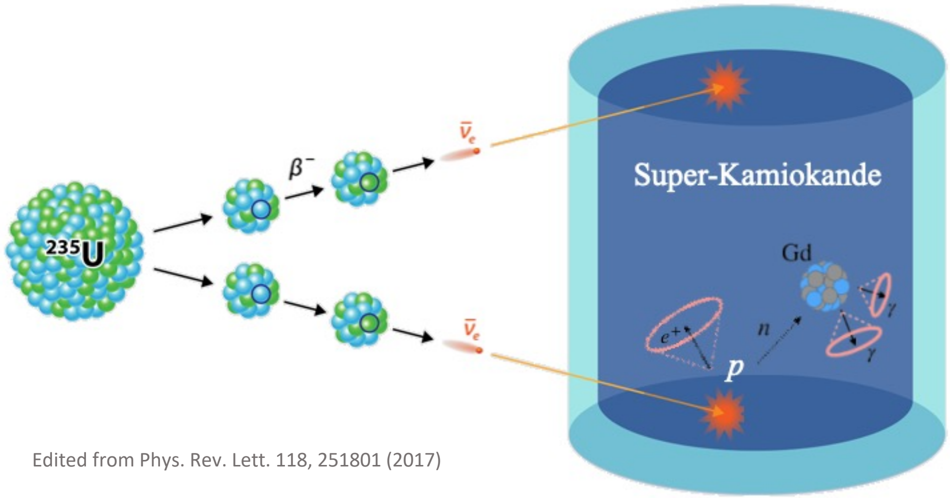
Since 2015, nuclear reactors have been restarting: 33 are currently active, 2 under construction, and 16 in process of restart approval.

[1]: https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx
[2]: https://www.iea.org/countries/japan

Reactor Neutrinos

The efficient neutron identification provided by gadolinium allows the search for signals from nuclear power reactors ($\bar{\nu}_e$ from fission products).

Primarily a result of the activity of Japanese nuclear power reactors (also small contribution from Korean reactors).



Edited from Phys. Rev. Lett. 118, 251801 (2017)

geoneutrinos.org

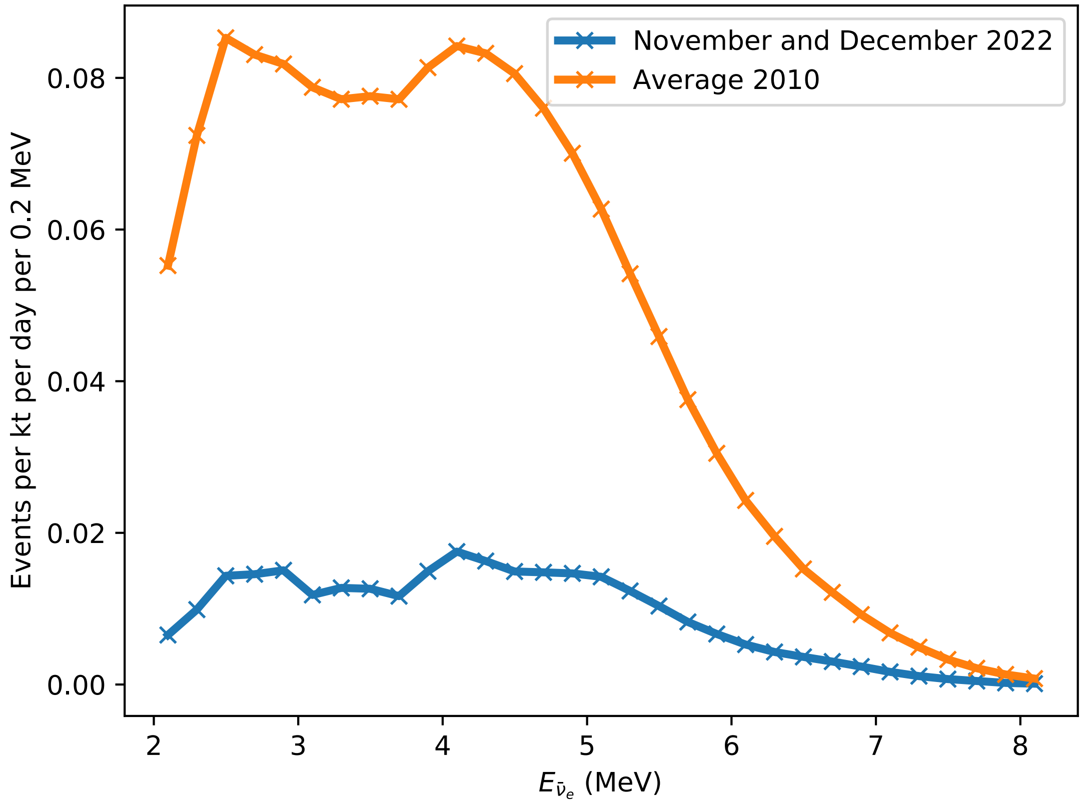
Expected Fluxes in Super-Kamiokande

Latest monthly load factor data provided by IAEA - Power Reactor Information System (PRIS): year 2022.

	Expected events/day in SuperK (22.5 ktons)
2010 (before Fukushima incident)	33 events
2022 November/December	7 events

Main contributions in Super-Kamiokande from nuclear reactors at the Wakasa-Bay:

- Mihama 3 (146 km)
- Ohi 3 and 4 (179 km)
- Takahama 3 and 4 (191 km)
- Takahama 1 (191 km)
  restarted on July 28th, 2023[1]
- Takahama 2 (191 km)
  restarted on September 16th, 2023[2]



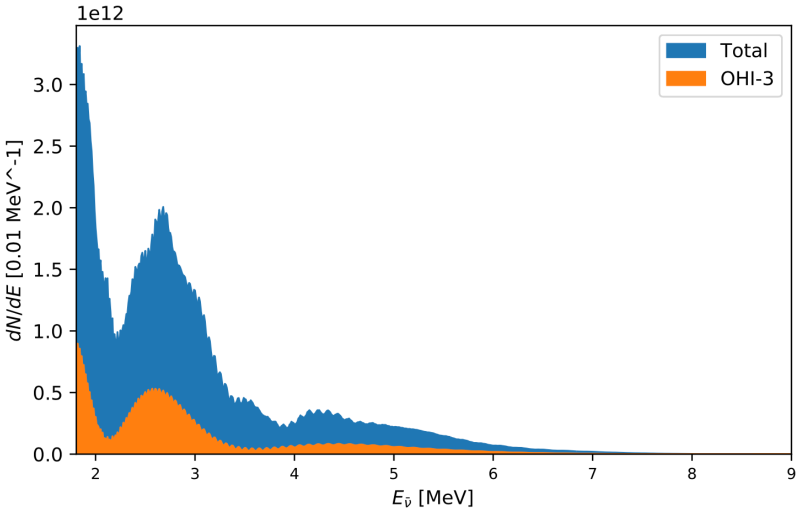
Averaged reactor flux under reactor activity assumptions for 2010 and November/December 2022. Reactor neutrino model used is Huber, Muller.

[1] https://news.yahoo.co.jp/articles/774b6d901e3a34d1f9519fe91b0bcea4e89a568c
[2] https://jp.reuters.com/world/japan/JTOB4FBMDZLC3FZ6TLLSWSKN5Q-2023-09-14

Reactor Neutrino Searches in SuperK (1/3)

The first reactor neutrino search conducted in SuperK used WIT data from December 2020 to October of 2021 (SK-VI period, with 0.01% Gd by mass)[1] . Nine nuclear reactors in Japan had restarted in this period Δ(rate) = 7.93d^{-1}.

- Reactor neutrino simulation package was created to simulate the reactor neutrino spectrum at SuperK: SKReact[2];
- Implementation of a coincidence trigger to WIT to tag IBD products;
- Two selection methods tested (SPLASH framework): standard cut-based and boosted decision tree.

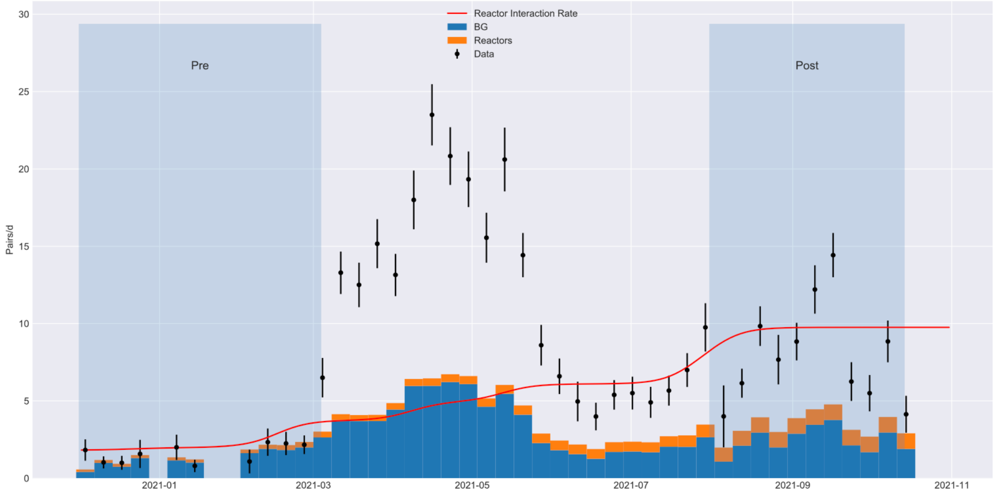


Simulated 2018 reactor spectrum at SuperK from SKReact.

Up to March 2021 of (1.6 ± 0.2) d^{-1};

Between March and August of 2021: unsteady data rates, inconsistent with data file properties;

From August 2021, results exceeded the predicted rates.



The work showed SuperK's capability to detect increases in reactor rate due to a reactor restart.

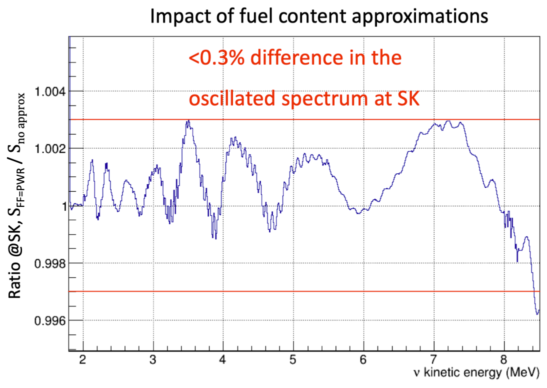
It also created a foundation for reactor neutrino searches in SK: data acquisition, modeling and analysis strategy.

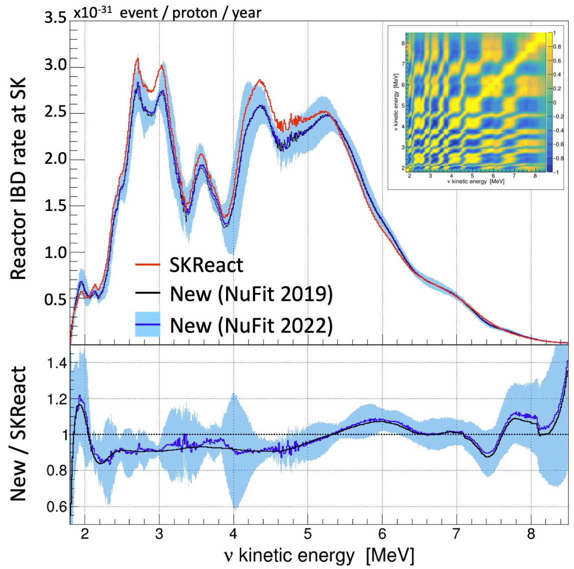
[1] Goldsack, A. (2022). Reactor neutrinos in a gadolinium-loaded Super-Kamiokande [PhD thesis].
[2] https://github.com/Goldie643/SKReact

Reactor Neutrino Searches in SuperK (2/3)

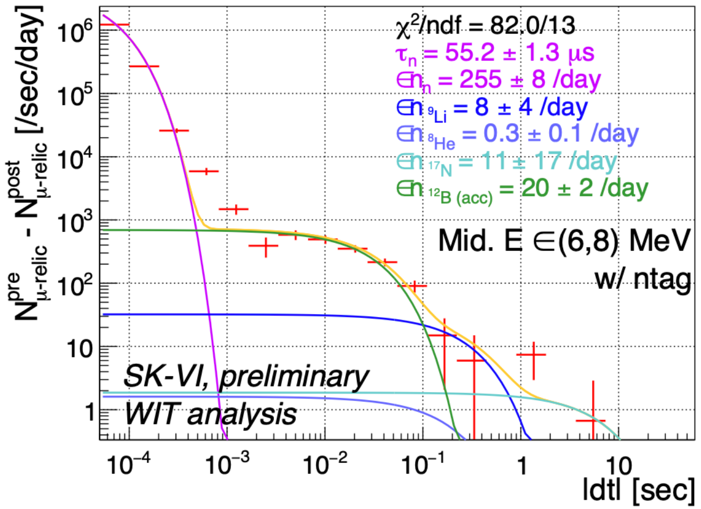
Currently on-going other searches/modeling:

1) New modeling, update SKReact (L. Perisse)
   - Better correlate physical processes to reactor spectra;
   - Use updated modeled spectra (e.g., reactor data driven model, summation model)
   - Study further Earth matter effect and $\bar{\nu}_e$ directionality



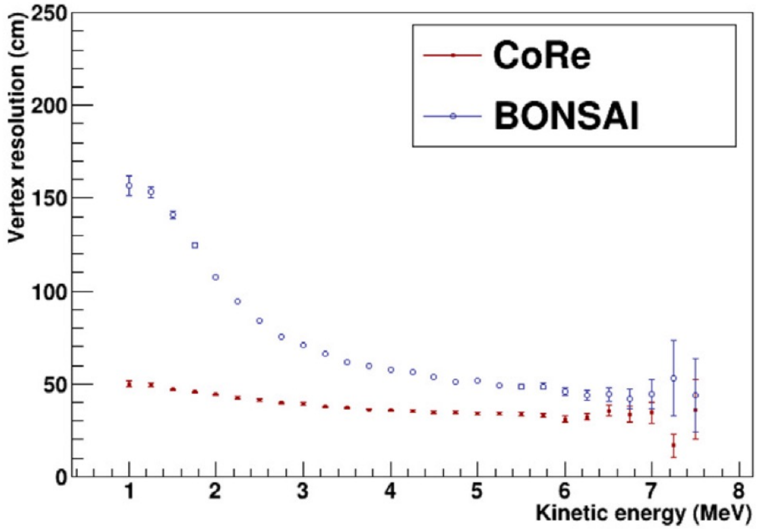


2) Lower energy extension for $\bar{\nu}_e$ region (S. Izumiyama)
   - Development of a new selection algorithm using low energy triggers (SLE and WIT) to lower conventional analysis thresholds;
   - Tested using AmBe data;
   - Observed spallation signal using algorithm;

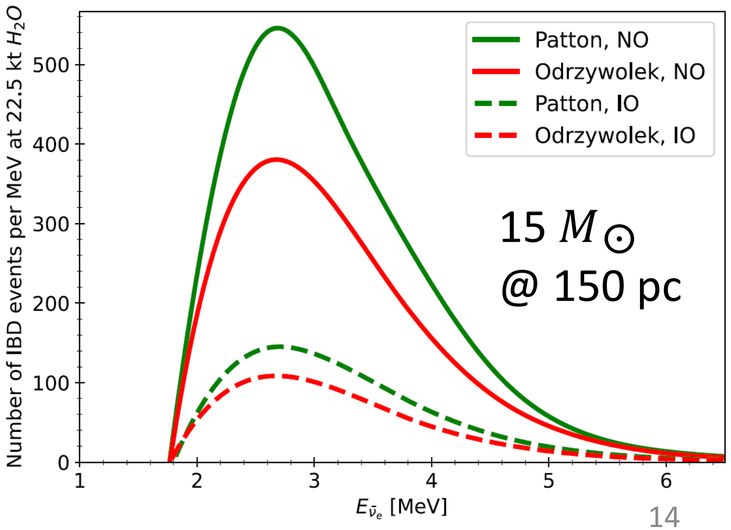


Reactor Neutrino Searches in SuperK (3/3)

3) Coincidence reconstruction for reactor $\bar{\nu}_e$ (L. Kneale)
   - Implementation of a dedicated IBD positron/neutron pair reconstruction "CoRe", for an accurate vertex reconstruction.
   - Using Monte Carlo, it improved vertex resolutions by a factor of 4.5 at lowest energies[1].
   - Currently adapting analysis to be used for reactor search in SuperK.



4) Searching for reactor $\bar{\nu}_e$ using the pre-supernova trigger (L. Machado)
   - Reactor neutrinos are in the same energy region as preSN neutrinos. SuperK has a running preSN alarm, designed to look for very low energy $\bar{\nu}_e$ [2].
   - Same analysis strategy is being applied to search for reactor neutrinos.
   - Studying if event rates observed by the preSN alarm correspond to reactor activity in Japan.



[1] L. Kneale et al Nucl.Instrum.Meth.A 1053 (2023) 168375
[2] L. N. Machado et al Astrophys.J. 935 (2022) 1, 40

Outlook

- Super-Kamiokande is a neutrino observatory running since 1996. It has a 50 kton water Cherenkov detector with 22.5 kton fiducial volume;
- 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 sources such as DSNB and pre-supernova stars.
- It also allows the detection of reactor neutrinos, as a result of the activity of Japanese nuclear power reactors in Japan. Main contributions to reactor flux in Super-Kamiokande are from nuclear reactors at the Wakasa-Bay (Ohi 3 and 4, Takahama 1, 2, 3 and 4, and Mihama 3);
- First search of reactor neutrinos using SK-Gd data showed Super-Kamiokande's capability to detect increases in reactor rate due to a reactor restart and created a foundation for reactor neutrino searches in SK: data acquisition, modeling and analysis strategy;
- Other reactor searches and modeling, as well as improvements in low energy trigger and reconstruction are on-going and we hope to observe a signal from reactor neutrinos soon.

BACKUP

Reactor Types

PRESSURIZED WATER REACTOR (PWR)

- Fuel: lowly enriched uranium (LEU), ^{238}U + 3-5% ^{235}U

$$^{238}_{92}\mathrm{U} \xrightarrow{(n,\gamma)} {}^{239}_{92}\mathrm{U} \xrightarrow[23.45\ \mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.35\ \mathrm{day}]{\beta^-} {}^{239}_{94}\mathrm{Pu} \xrightarrow{(n,\gamma)} {}^{240}_{93}\mathrm{Np} \xrightarrow{(n,\gamma)} {}^{241}_{93}\mathrm{Pu}$$

- High power: ~3 - 4 GW_{th}
- Close reactor design & fuel contents for all PWR

⇒ Similar $\bar{\nu}_e$ spectra

		$\Phi_{\bar{\nu}_e}$ [$\bar{\nu}_e$/fis]	Contribution [%]	
Fission	^{235}U	**3.3**	**46.3**	~83%
	^{239}Pu	**1.7**	**24.1**	
	^{238}U	0.5	7.3	
	^{241}Pu	0.4	5.1	
Activation	^{239}U	0.6	8.6	~17%
	^{239}Np	0.6	8.6	
Total		**7.2**	100	

Typical average flux/fission for a PWR type reactor (~4% ^{235}U) over a 12-month core cycle

OVERVIEW OF REACTOR TYPES AT SK

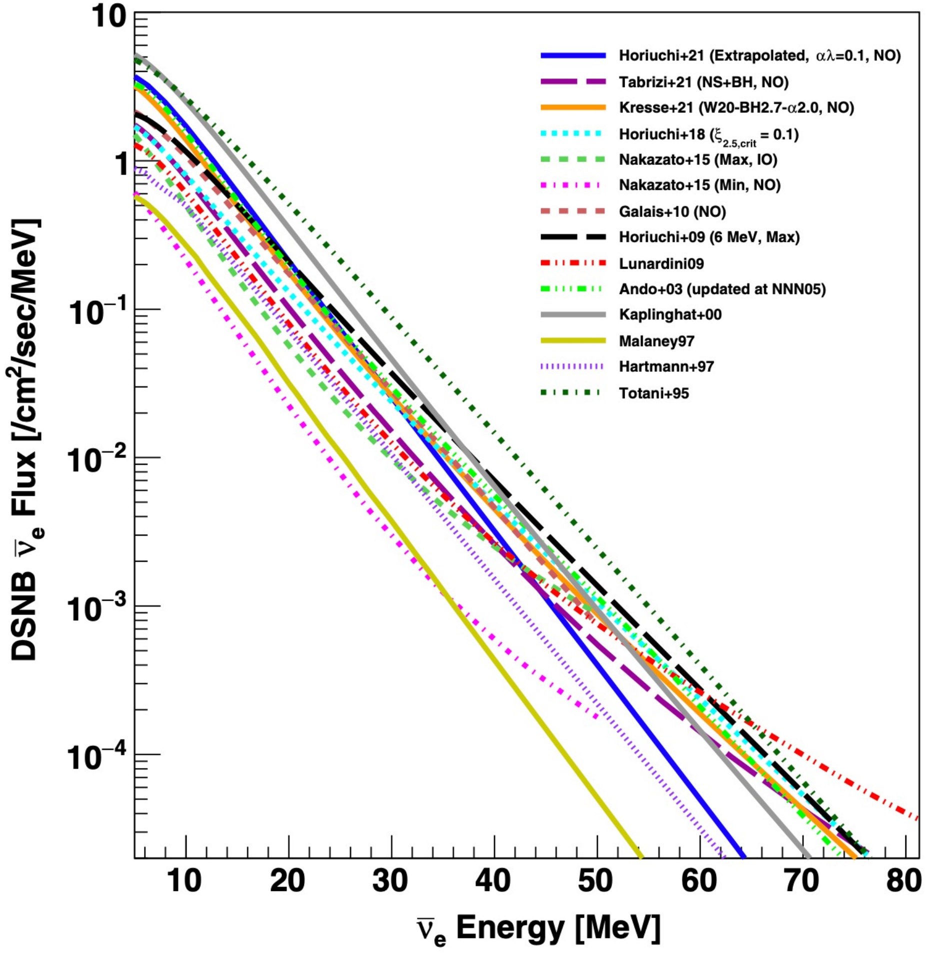
Type	Fuel	Active reactors in the world[1]	Avg monthly power[1] (mean, total)	Avg monthly contribution to SK $\Phi_{\bar{\nu}_e}$ [%][1]
Pressurized Water Reactor (PWR)	LEU	294	2.1 GW_{th} 645.0 GW_{th}	96
Pressurized Heavy Water Reactor (PHWR)	NU*	46	1.3 GW_{th} 63.7 GW_{th}	3
Boiling Water Reactor (BWR)	LEU (~PWR)	48	2.0 GW_{th} 129.3 GW_{th}	~ 8E-1
Mixed Oxyde Reactor (MOX)	$PuO_2 + UO_2$#	29 $\left(\begin{smallmatrix}1\ \mathrm{BWR}\\28\ \mathrm{PWR}\end{smallmatrix}\right)$	2.1 GW_{th} 65.4 GW_{th}	~ 2E-1
Light Water cooled Graphite moderated Reactor (LWGR)	SEU*/LEU	13	1.9 GW_{th} 24.7 GW_{th}	~ 1E-1
Graphite moderated Gas cooled Reactor (GCR)	very LEU/ NU*	14	0.8 GW_{th} 11.3 GW_{th}	~ 5E-2
Fast Breader Reactor (FBR)	$PuO_2 + UO_2$	2	1.5 GW_{th} 3.0 GW_{th}	~ 3E-2
Research Reactor (RR)	HEU	No data	<100 MW_{th} 2.2 GW_{th}	< 1E-3

[1] From 2020 INFN data (dataset used in all this presentation)
** Slightly enriched uranium, Natural uranium*
 # Natural, reprocessed or depleted uranium

Courtesy of L. Perisse

Diffuse Supernova Neutrino Background (DSNB)

Accumulated flux of neutrinos emitted from past all Supernovae.

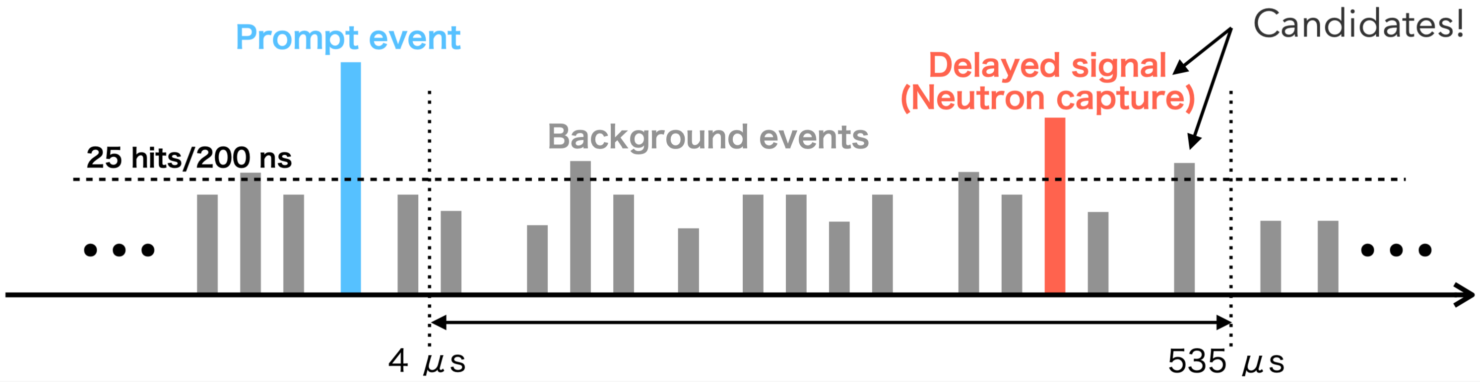


First search of DSNB using SK-Gd data (from SK-VI, 0.01% Gd):
M. Harada et al 2023 ApJL 951 L27

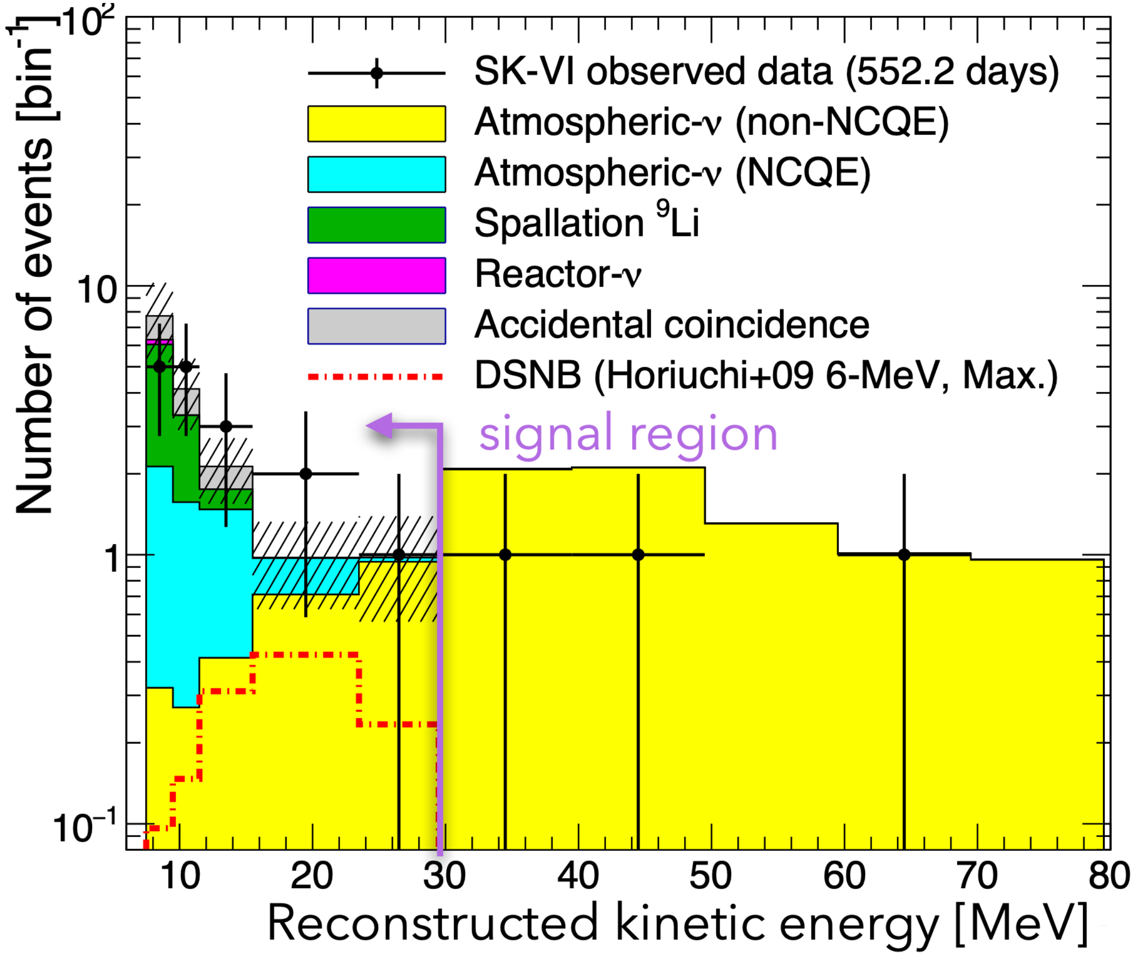
Data set:

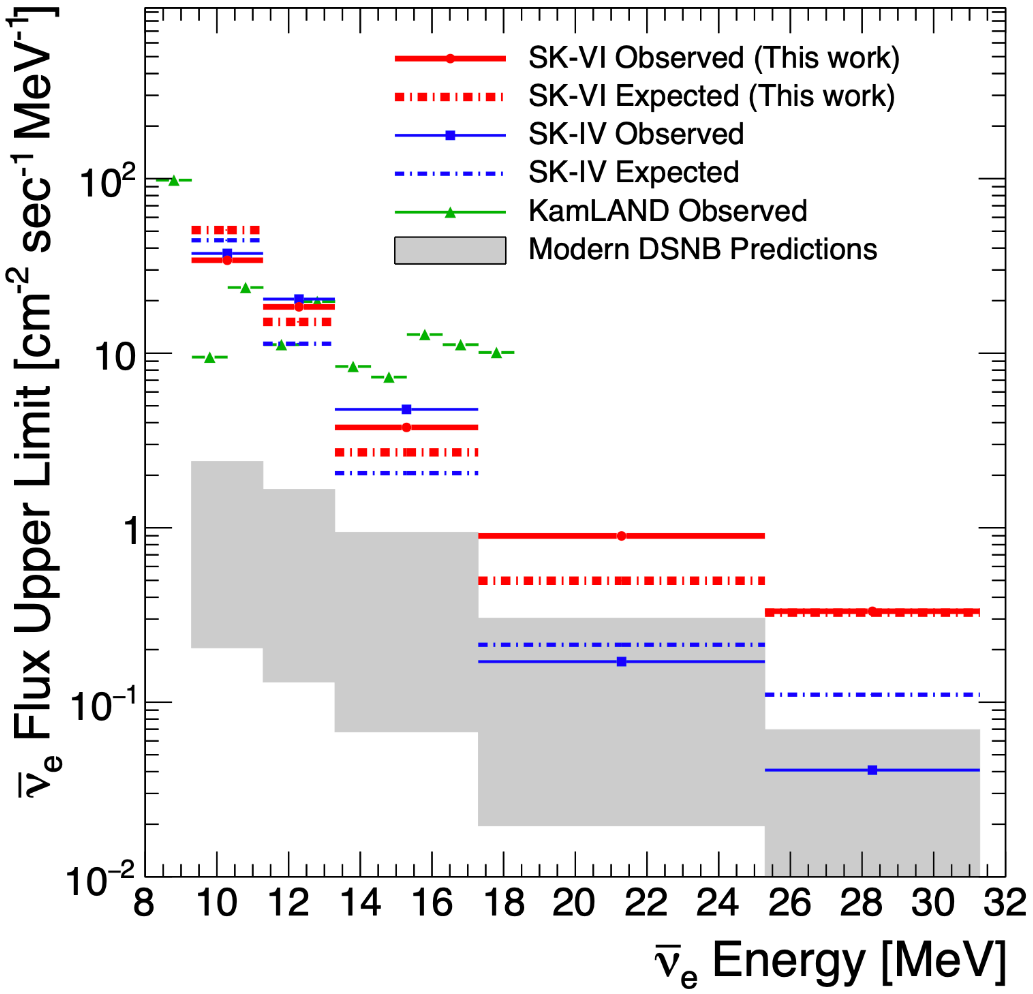
- Aug. 2020 — Jun. 2022 → 552.2 days × 22.5 kton FV
- Neutrino energy: 9.3 – 31.3 MeV (positron energy : 8-30 MeV)

Search neutron candidates using a 25 hits/200ns threshold.



Diffuse Supernova Neutrino Background (DSNB)

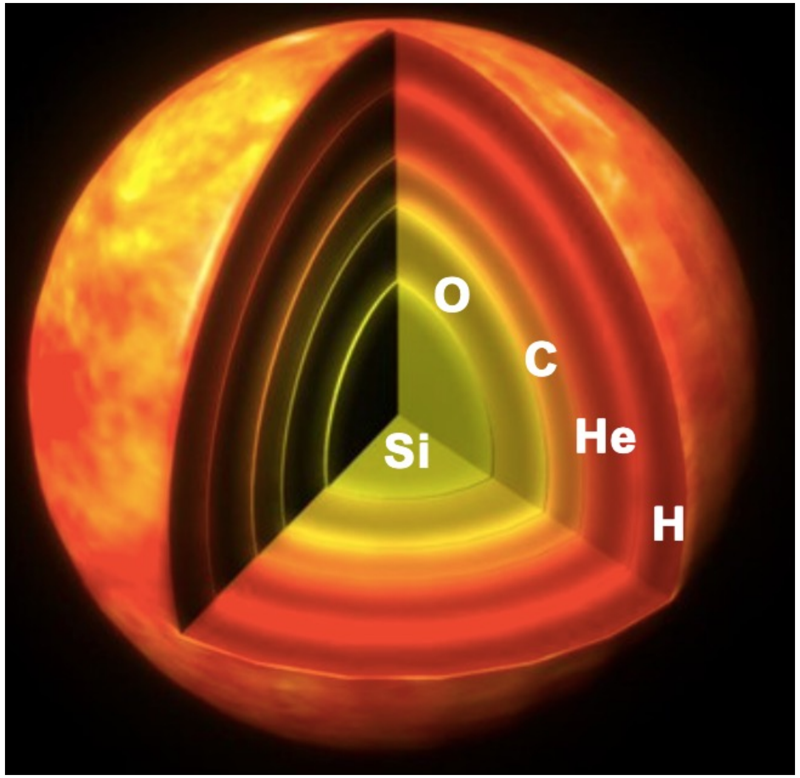




No excess over the expected background. Upper limit comparable to pure water phase, using live time 5 times smaller.

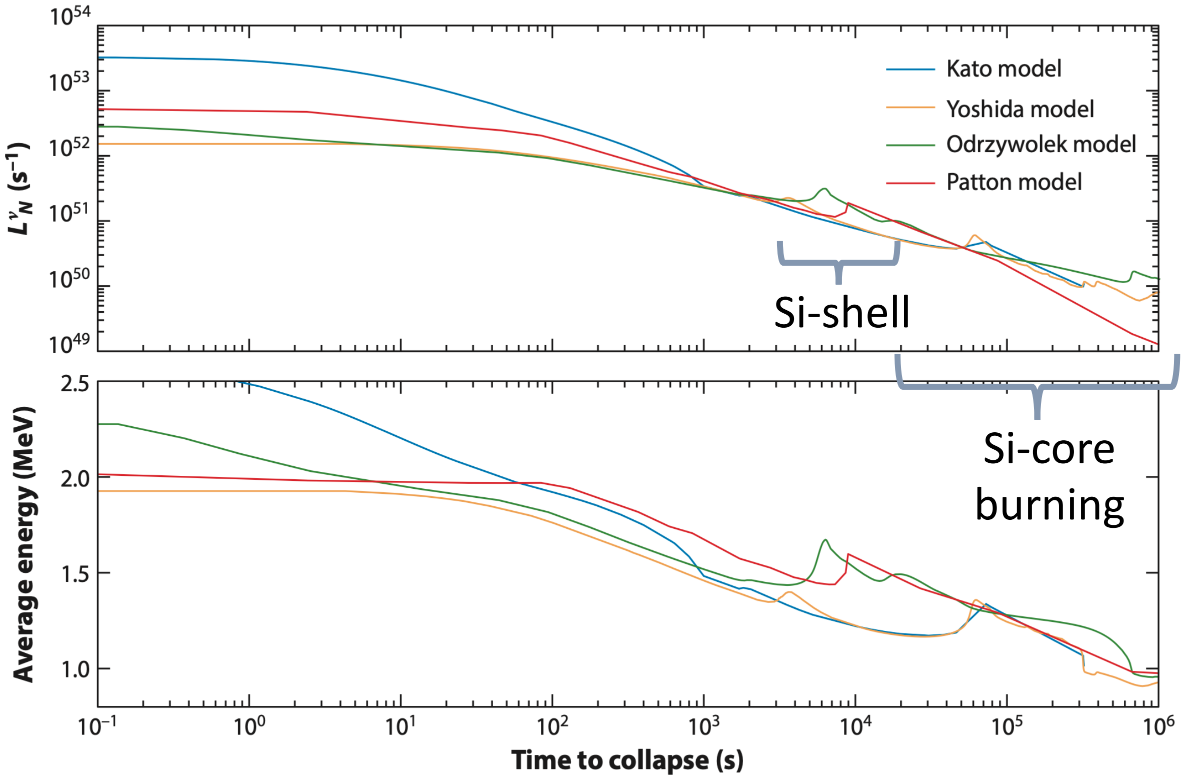
Pre-Supernova (Si-burning) Stars

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 $\sim 10^{5}\ L_\odot$

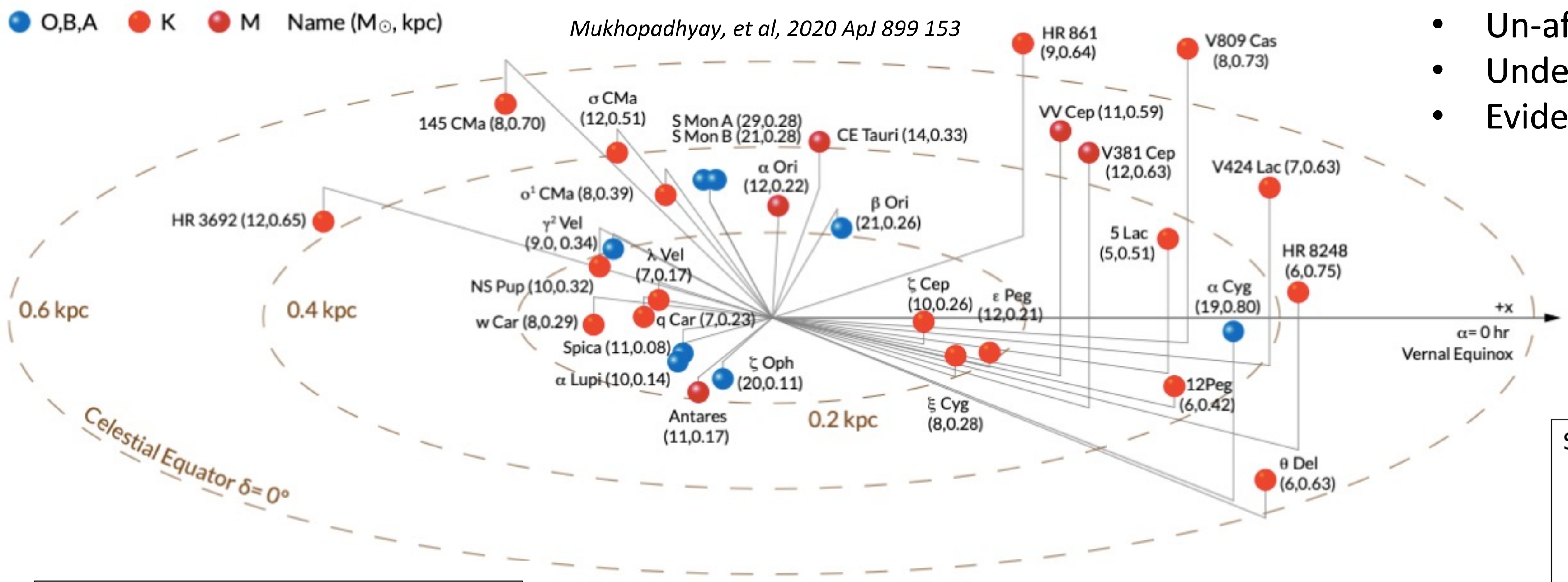
The last stage of these stars before the core-collapse is the **Si-burning** phase and it is expected to last for a **few days**.



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

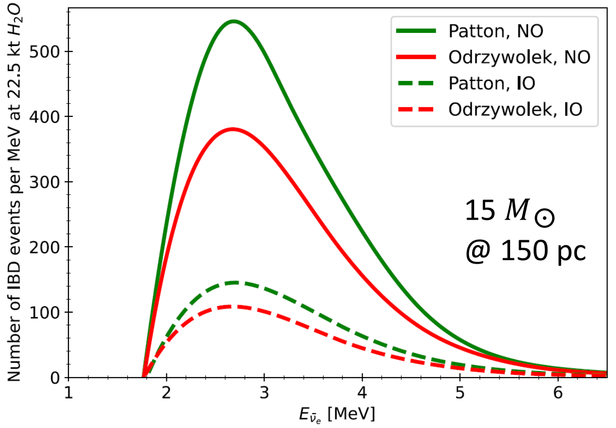
Neutrino production mainly from electron-positron annihilation.

Pre-Supernova Neutrinos in SK-Gd



- Un-affected observation of the interior of stars;
- Understand physical processes leading to CCSN;
- Evidence for neutrino mass ordering;

Early warning system for supernovae running in Super-Kamiokande since October 22nd, 2021.

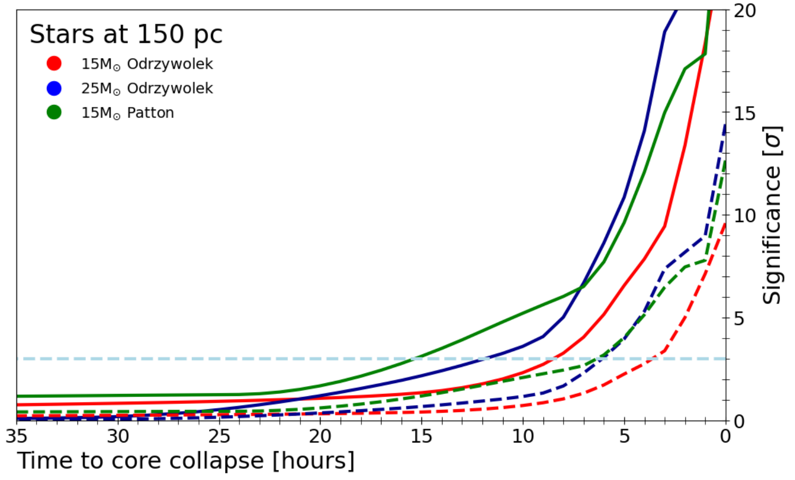


Number of pre-supernova IBD interactions in the 22.5 kt SK FV integrated over the last 10 hr prior to the CCSN

Super-Kamiokande and KamLAND have combined both pre-supernova alarms.

Extend most optimistic warning for Betelgeuse:
15 hours → 20 hours

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



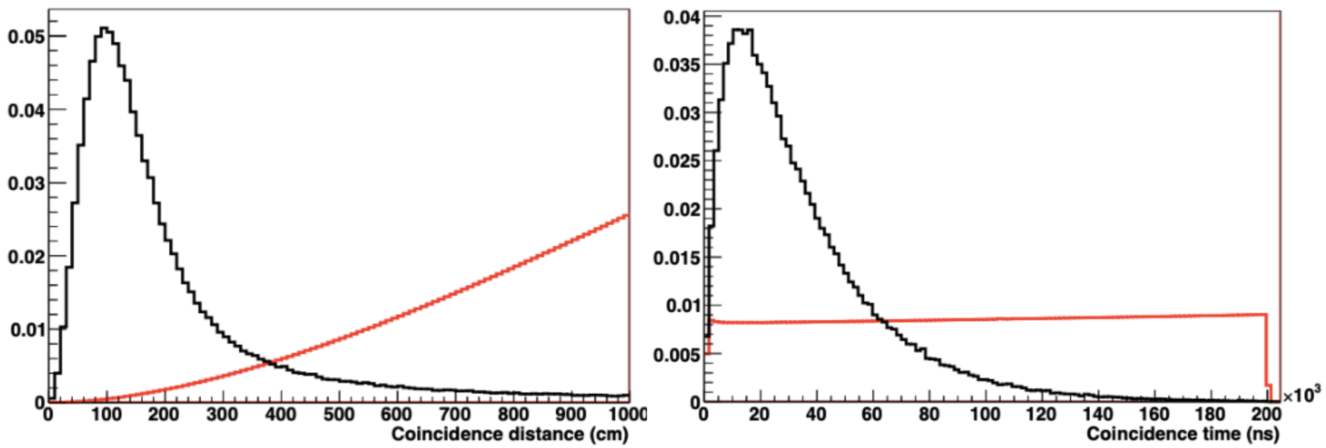
Evolution of the significance level in Super-Kamiokande with 0.03% Gd

Pre-supernova Alarm – Selection

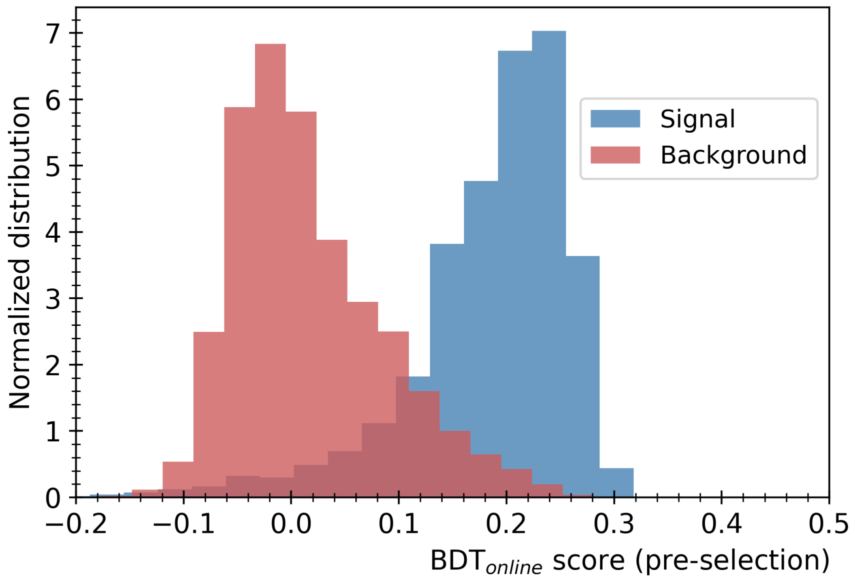
Mainly based on dR, dT and BDT. Regularly updated to consider the detector conditions.

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.



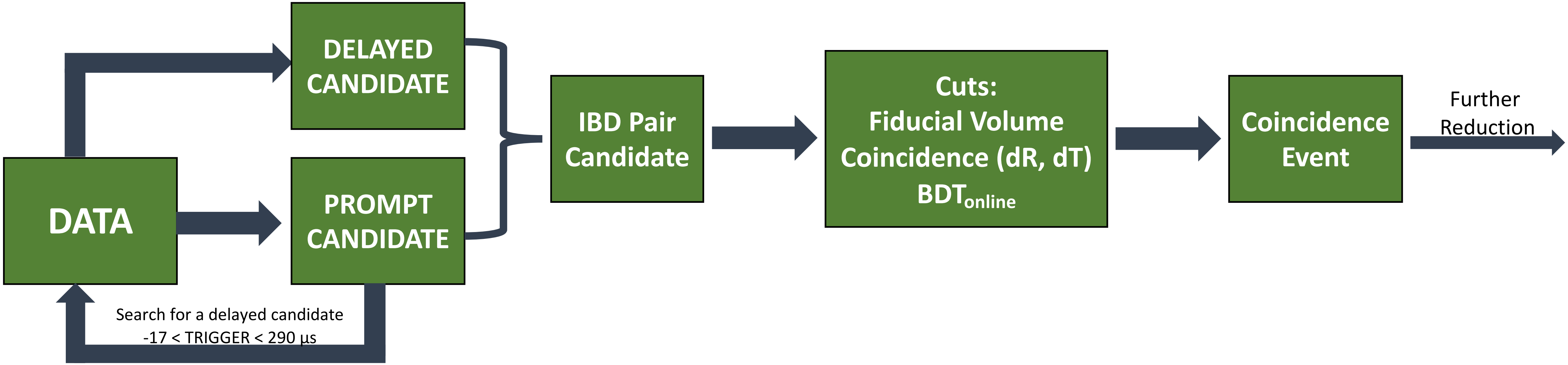
Coincidence Time and Distance between products from IBD events for simulated signal (black) and background (red).



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:



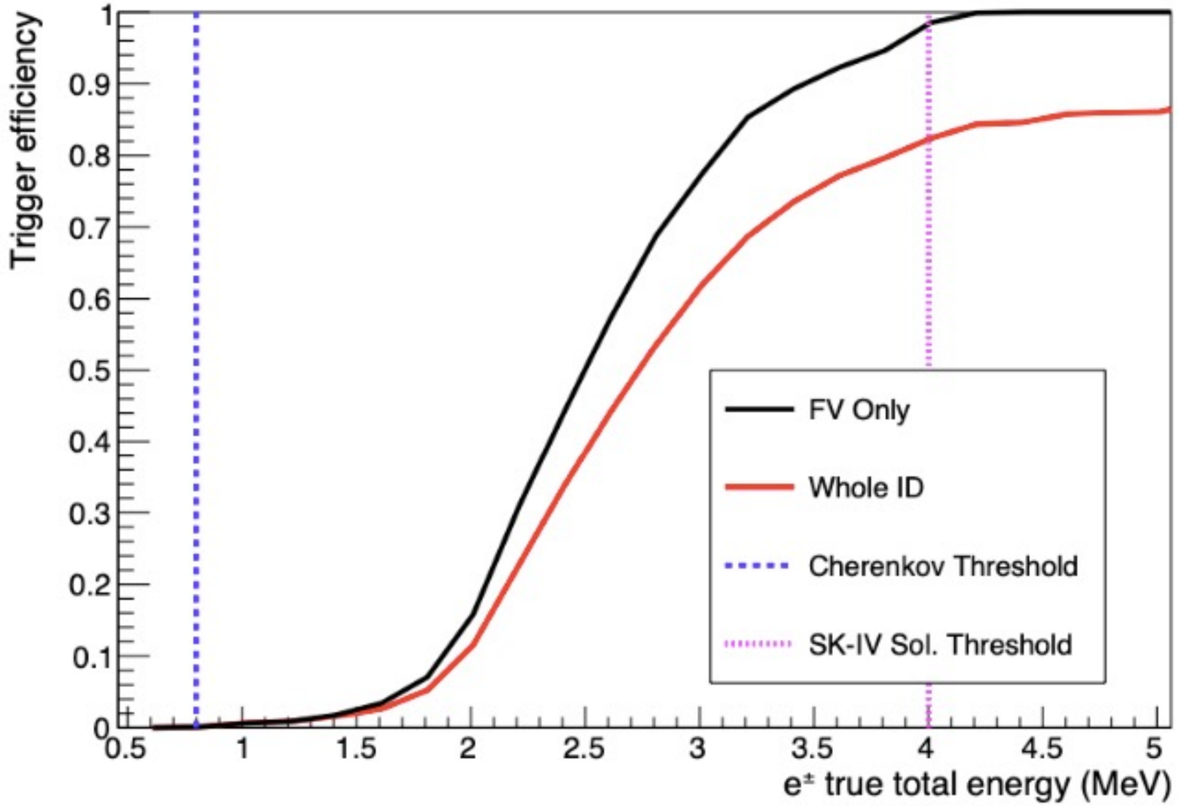
The BDT_{online} also improved the sensitivity for the pre-Supernova detection.

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