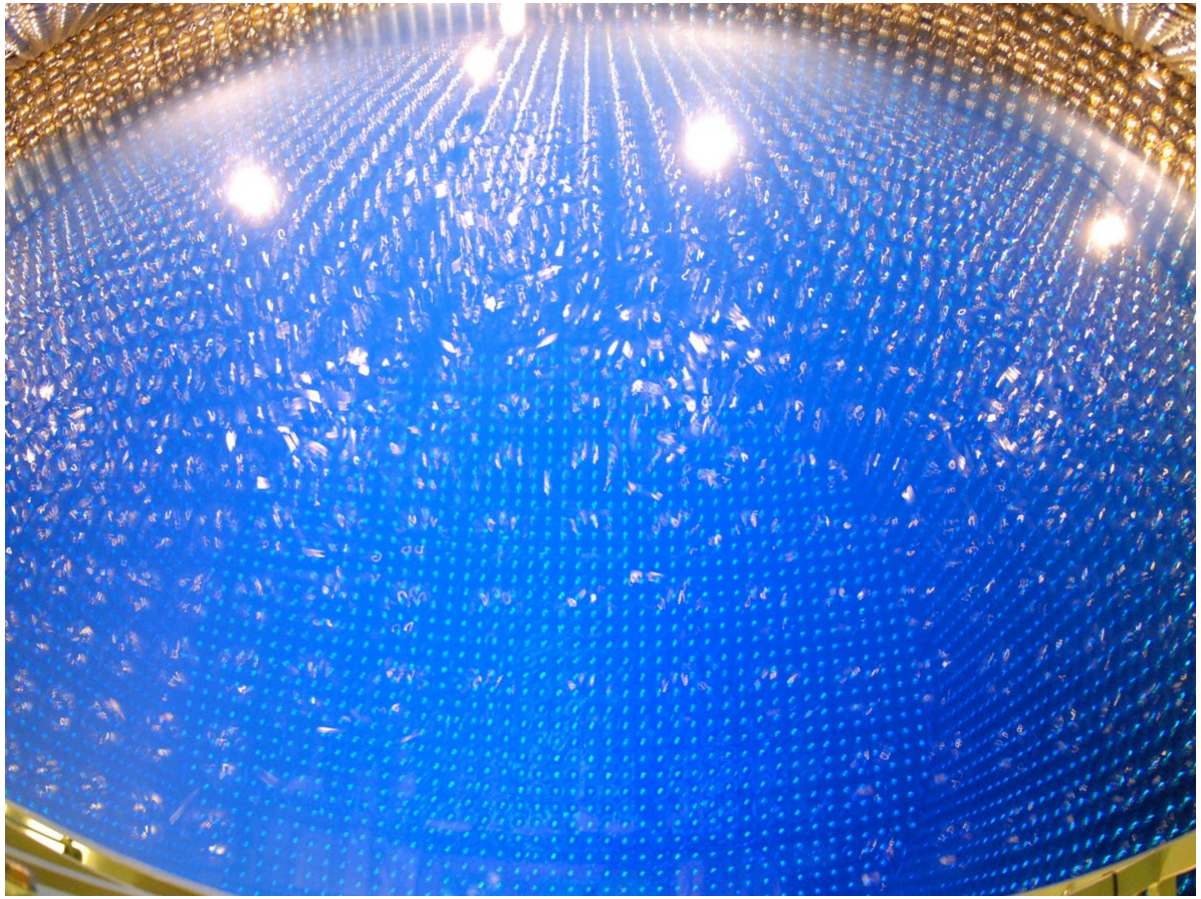
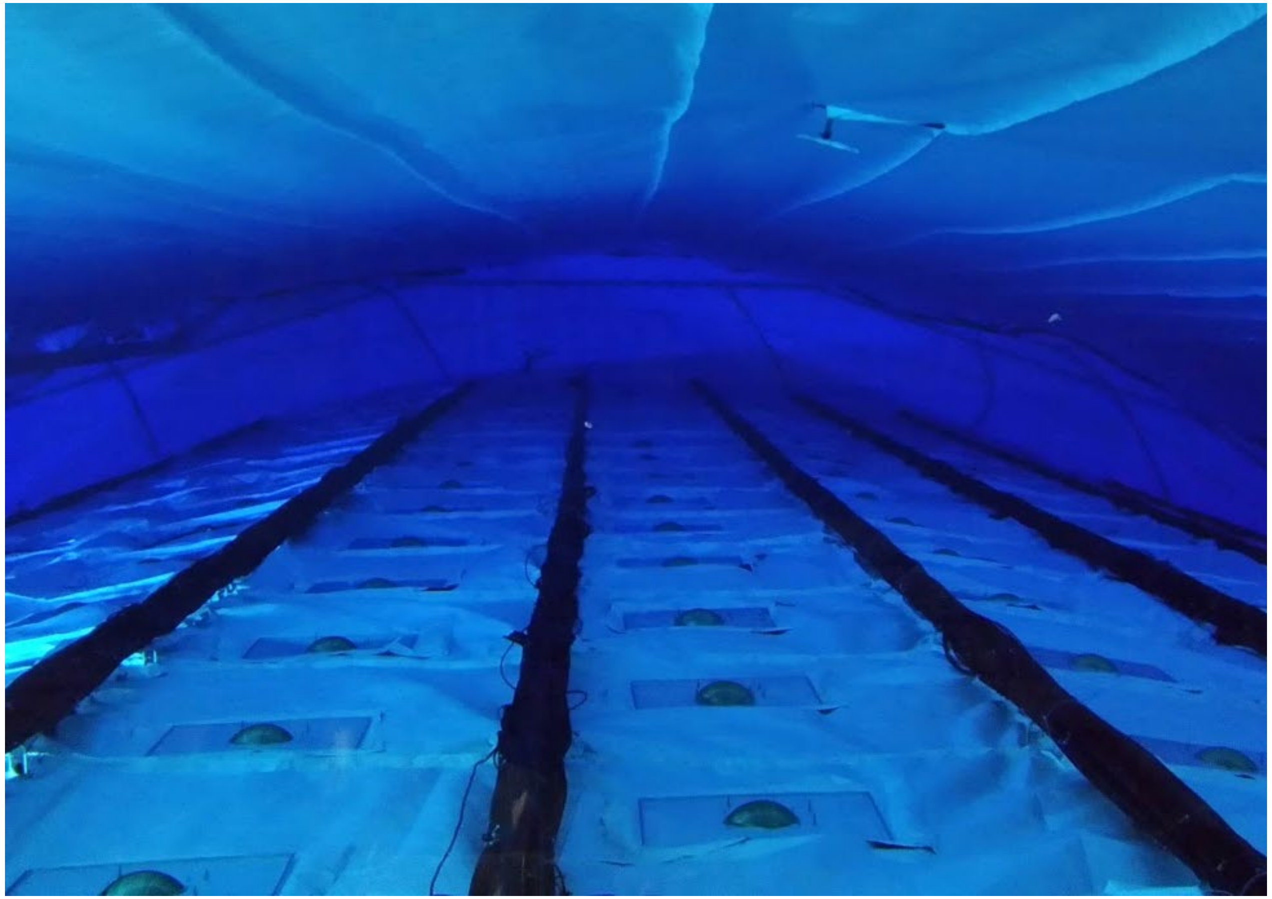



Super-Kamiokande

II EU Workshop on Water Cherenkov Experiments for Precision Physics

September 17, 2025

Hiroyuki Sekiya

for the Super-Kamiokande Collaboration

The Super-Kamiokande Collaboration

~240 collaborators
from 55 institutes
in 11 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan
INFN Bari, Italyl
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Institute of Science Tokyo, Japan
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
NIT, Numazu college, Japan
Okayama University, Japan
Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

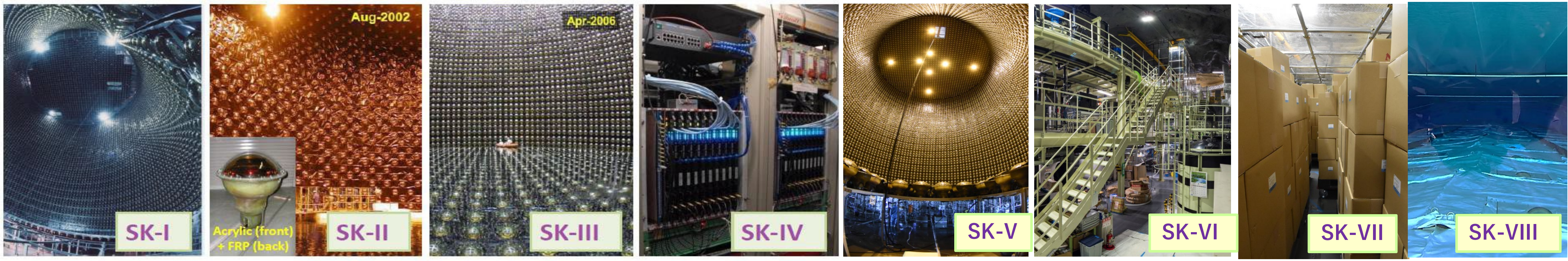
Super-Kamiokande History

SK will celebrate its 30th anniversary in 2026

SK-Gd

1996 | 2002 | 2006 | 2008 | 2018 | 2019 | 2020 | 2022 | 2024

SK-I | SK-II | SK-III | SK-IV | SK-V | SK-VI | SK-VII | SK-VIII



0.01%Gd   0.03%Gd

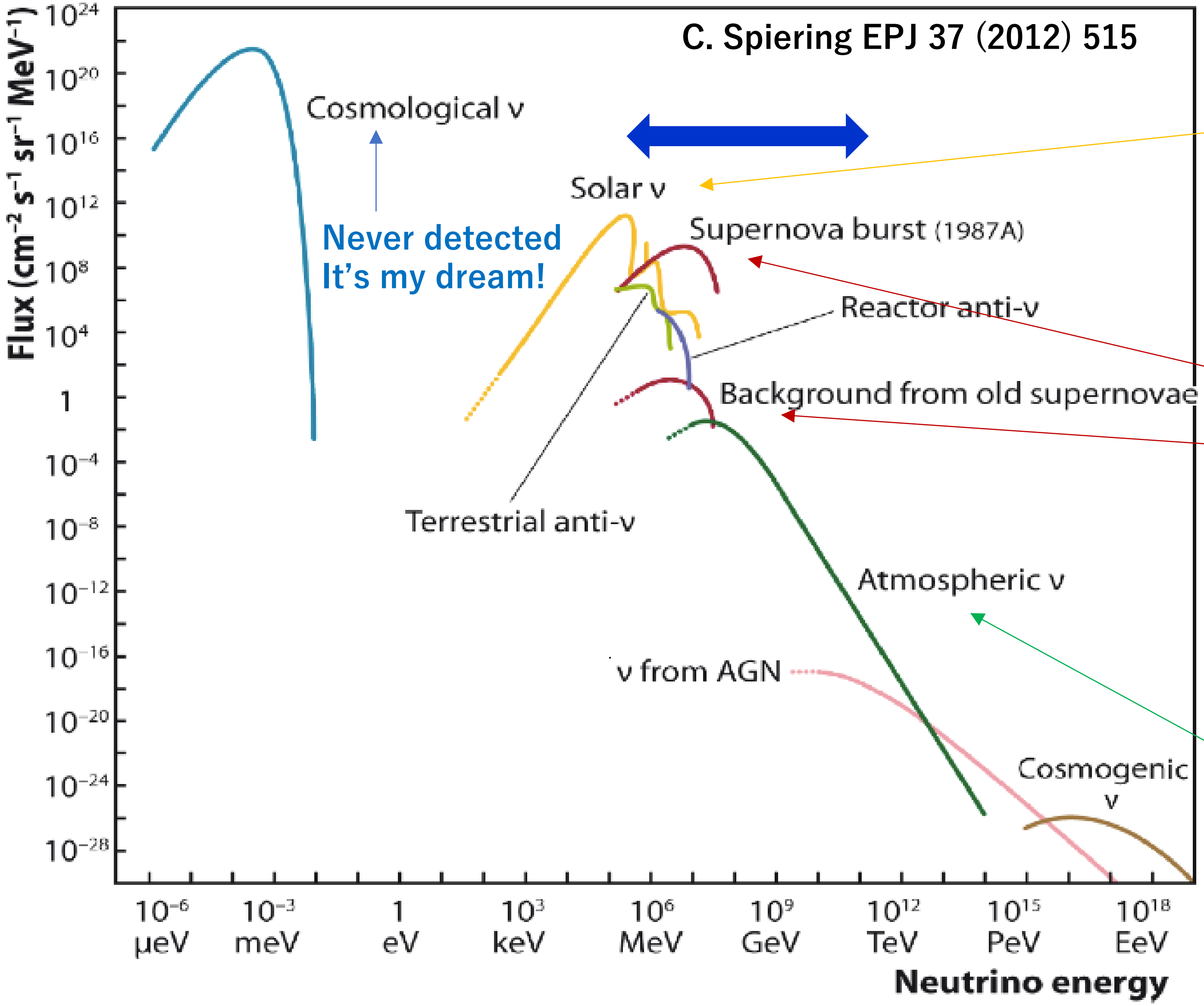
Pure water

Total live time for current oscillation analysis:
5805 days (SK-I~IV, for solar)
6511 days (SK-I~V, for atmospheric)

Gd-loaded water

Live time for DSNB search:
956.2 days + the future…

Targets of SK-Gd



(Energy: Kinetic energy)

Solar neutrinos

3.5~ 20 MeV

~15 events/day

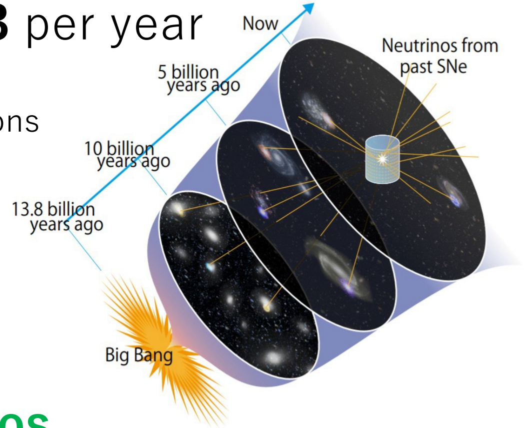
Supernova neutrinos

A few ~ 20 MeV →**Never detected in SK**

Several thousand events (for 10kpc)

Expect a few **DSNB** per year

Neutrinos from
past supernova explosions



Atmospheric neutrinos

100 MeV ~ a few 100 GeV

~ 10 events/day

Diffuse Supernova Neutrino Background

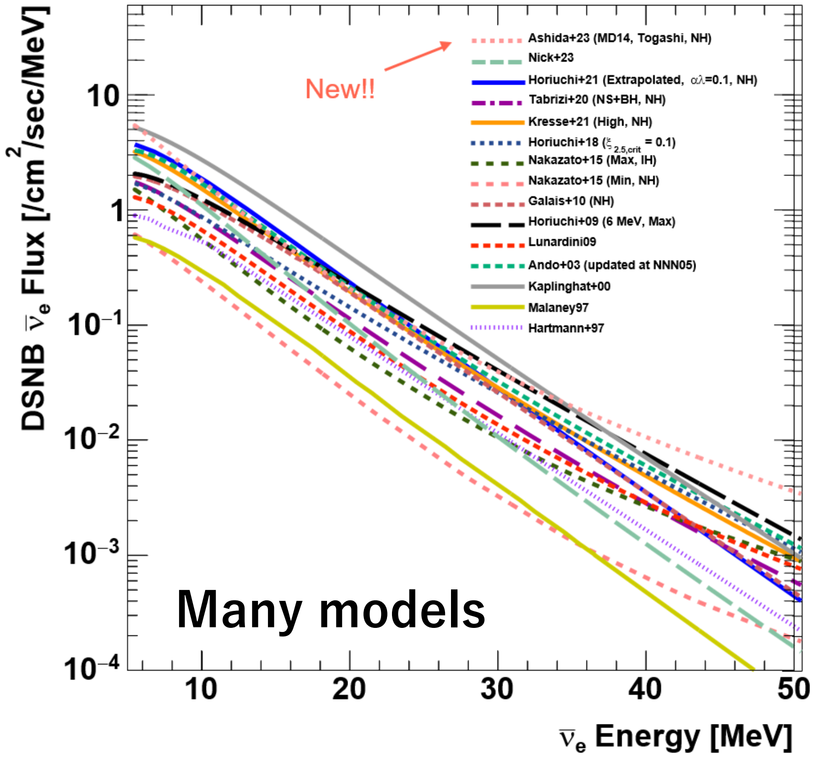
Supernova Relic Neutrino

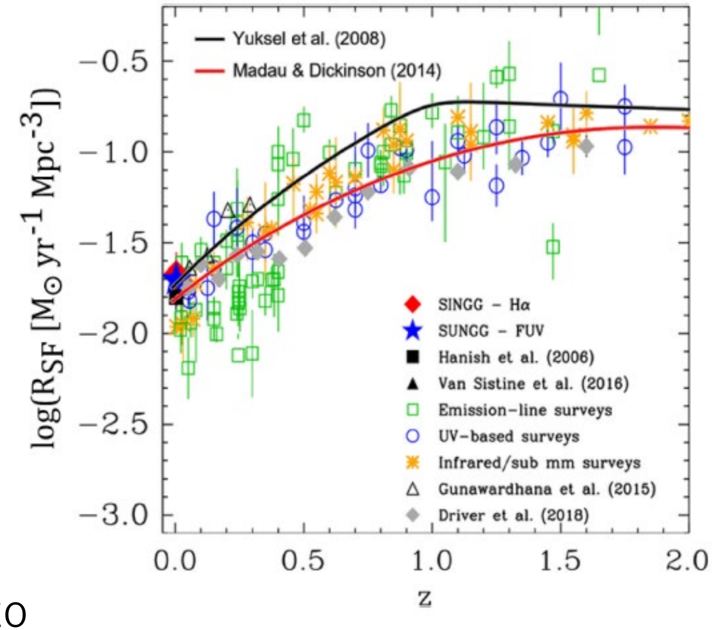
Neutrinos emitted in past supernova explosions and stored in the current universe → **promising extra-galactic ν**

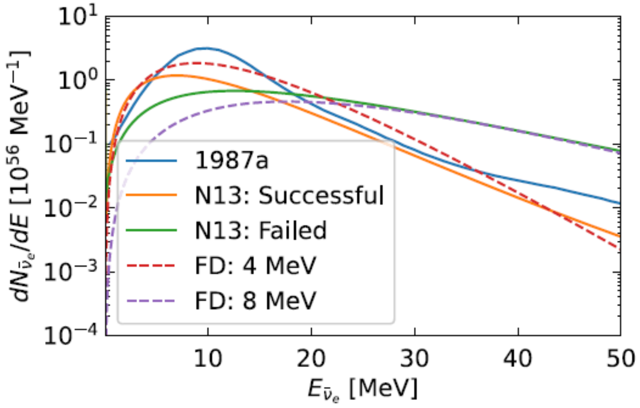
- In the entire universe, several supernova explosions occur every second.
- There must have been $O(10^{18})$ explosions in the history of the universe.

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SN rate at z **(averaged)SN spectrum**







Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

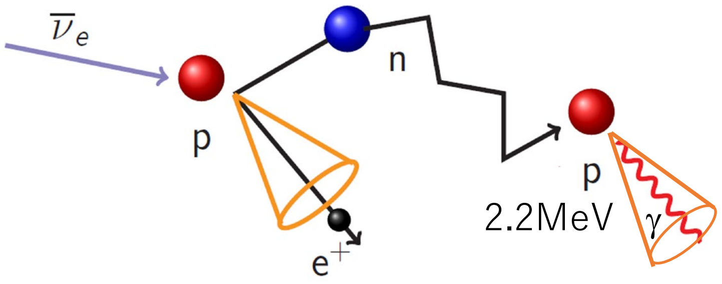
Access to
- ✓ **History of Star Formation**
- ✓ **BH formation**
- ✓ **Mechanism of the supernova explosion**

DSNB "signal" search in SK

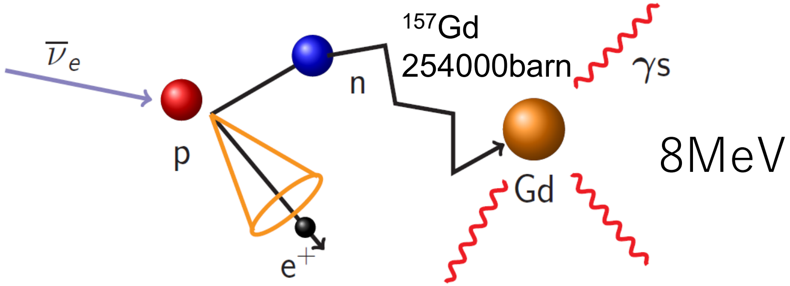
- **Search for inverse-beta decay (IBD)** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Largest cross-section @ DSNB signal range
  - Simple event topology: 1 positron and 1 neutron

→ **Require only one delayed neutrons signal**

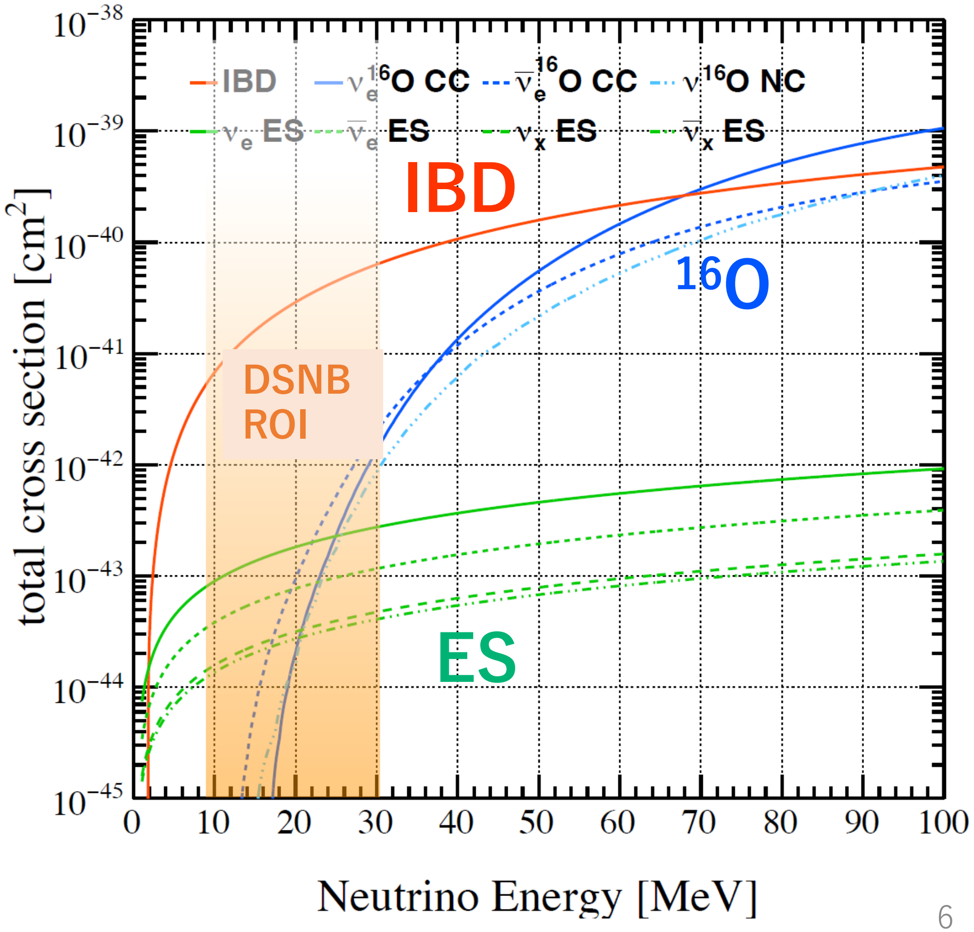
In pure water, the neutron tagging efficiency is low.



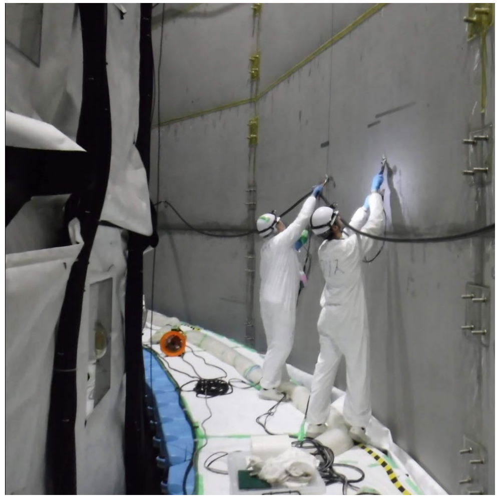
Gd-loading improves neutron tagging efficiency.



The interaction channels

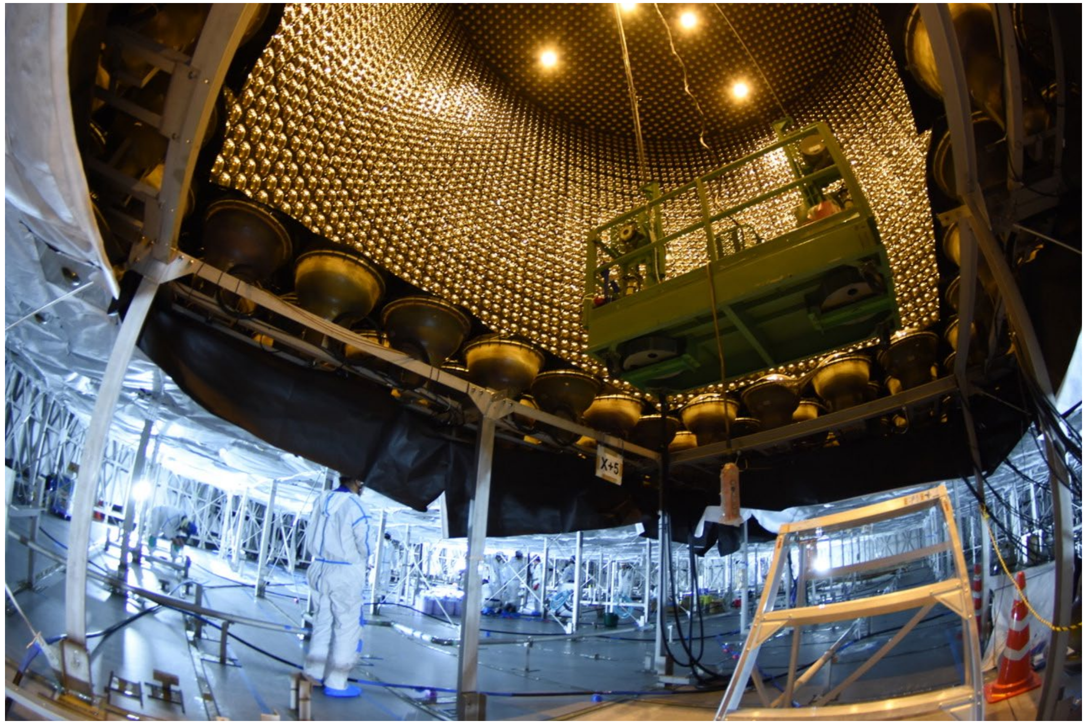


Major Challenges for SK-Gd



- Repair of the SK tank to fix the leakage
- $Gd_2(SO_4)_3$ -water system
- Radio isotopes in $Gd_2(SO_4)_3 \cdot 8H_2O$

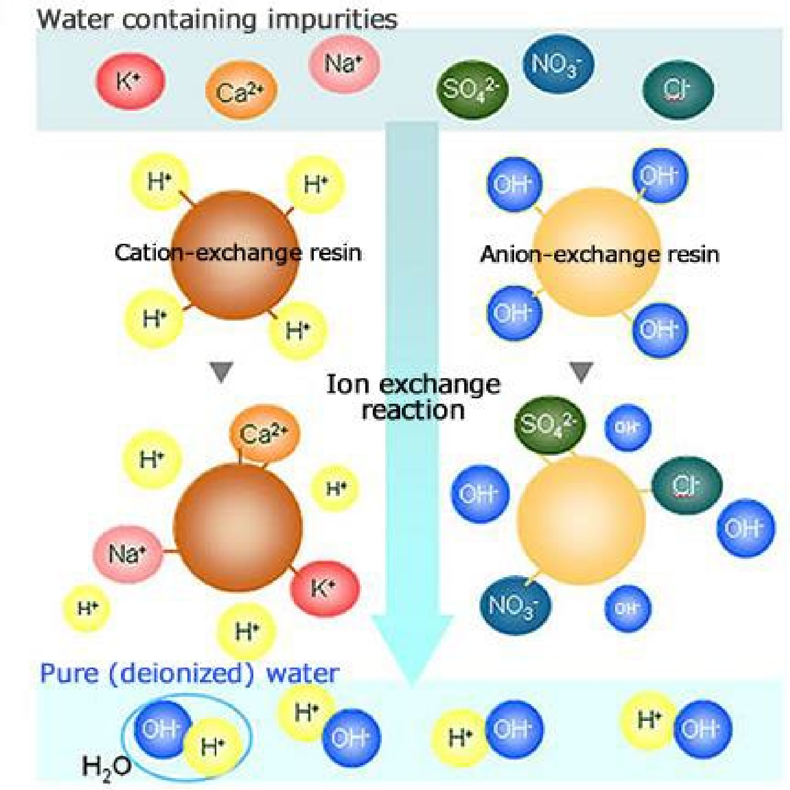
SK tank refurbishment in 2018



Water purification

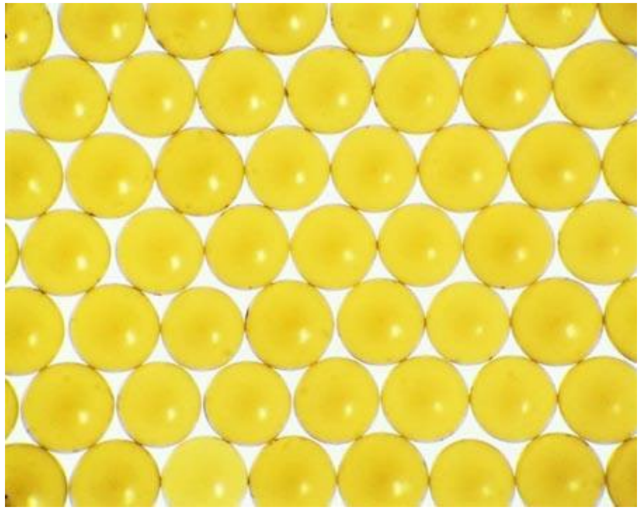
Gd sulfate could not be doped with the original SK water system designed to remove all the impurities other than H_2O.

Key technology:
Ion exchange resin



Development of special ion exchange resins
Anion exchange resin $OH^- \rightarrow SO_4^{2-}$
Cation exchange resin $H^+ \rightarrow Gd^{3+}$

RI impurities (Ra^{2+}, $UO_2(SO_4)_3^{4-}$ etc.) are also removed.



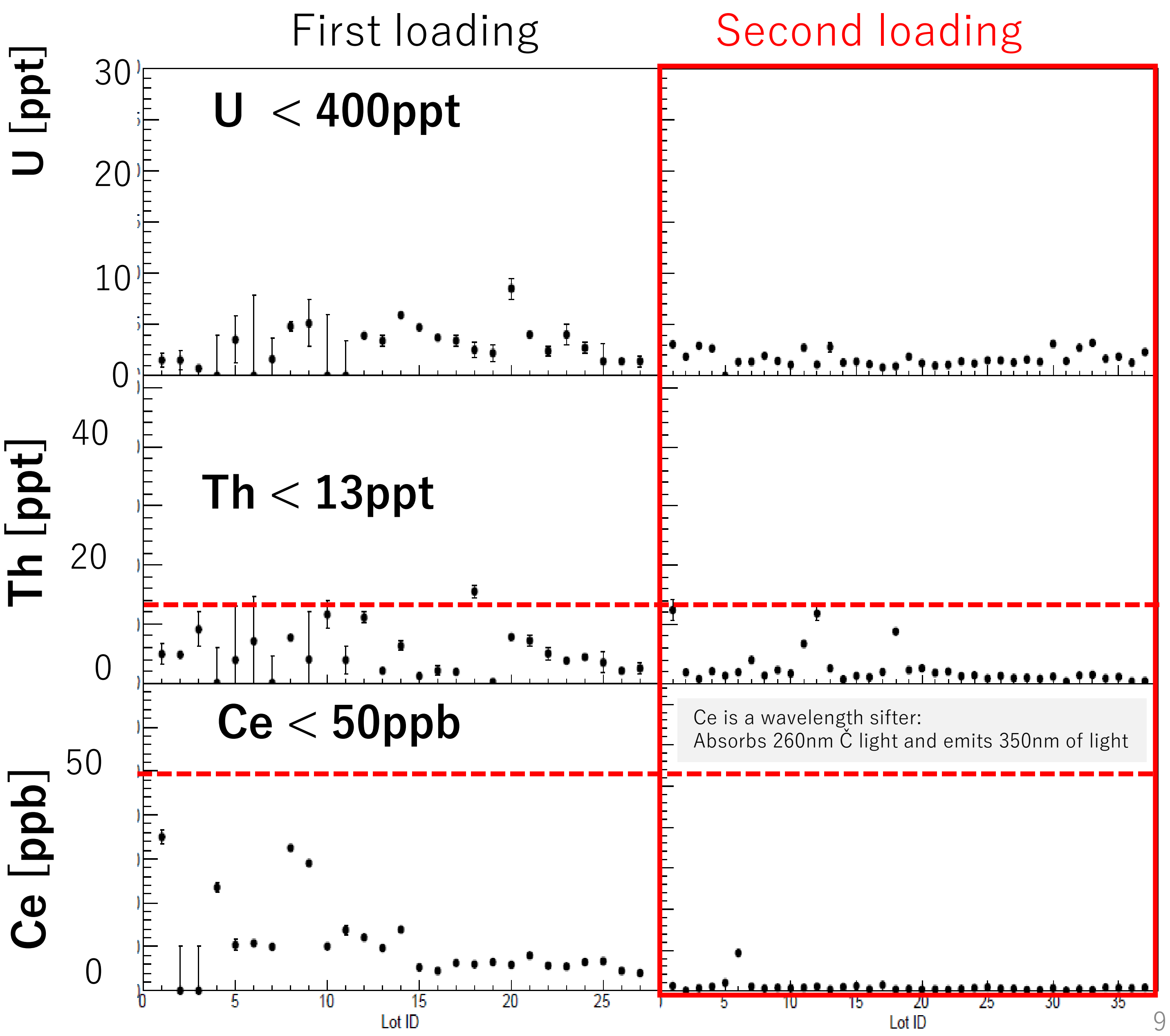
Pure Gd

PTEP 2023 (2023) 1, 013H01

- **Development with NYC,**
  - 日本イットリウム株式会社 Nippon Yttrium Co.,ltd.
  - Pure Gd_2O_3
    - Further purification of Gd_2O_3 for the second loading
  - Solvent extraction
  - Neutralization and sulfation
- **Evaluation with Boulby, Canfranc, and IBS CUP**
  - Lots of Ge detectors were needed to evaluate all the batches of the feedstock of Gd_2O_3 and the production LOTs of the $Gd_2(SO_4)_3 \cdot 8H_2O$

Collaboration with

Kamioka ICP-MS result with the requirements

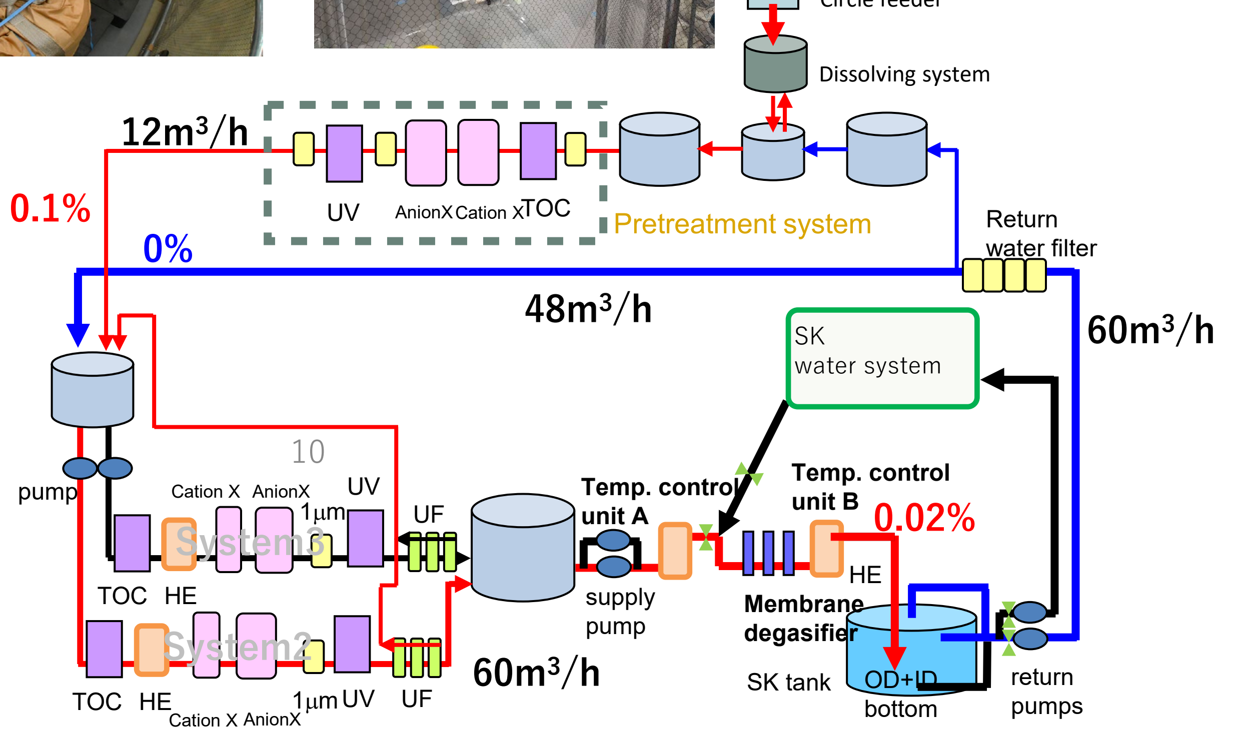


The 1st Gd-loading Jul. 14 – Aug. 18, 2020

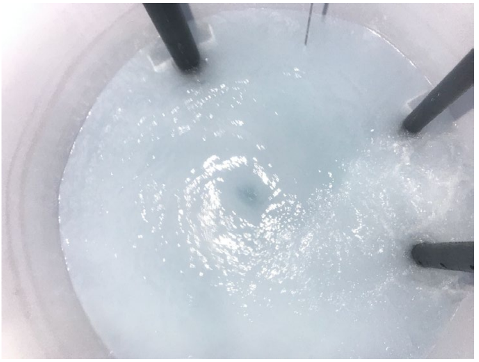
The pure water in the SK tank was taken from the top and returned from the bottom in **0.02% $Gd_2(SO_4)_3$** solution **(=0.01% Gd = 0.026% $Gd_2(SO_4)_3 \cdot 8H_2O$**)
It took 35 days to replace 50,000 tons of water at 60 m^3/h

One batch:
8.2 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$
+ 768 L of SK water = total 13 tons

Repeated every 30 minutes for 24 hours for 35 consecutive days



Just after mixing



10minutes later

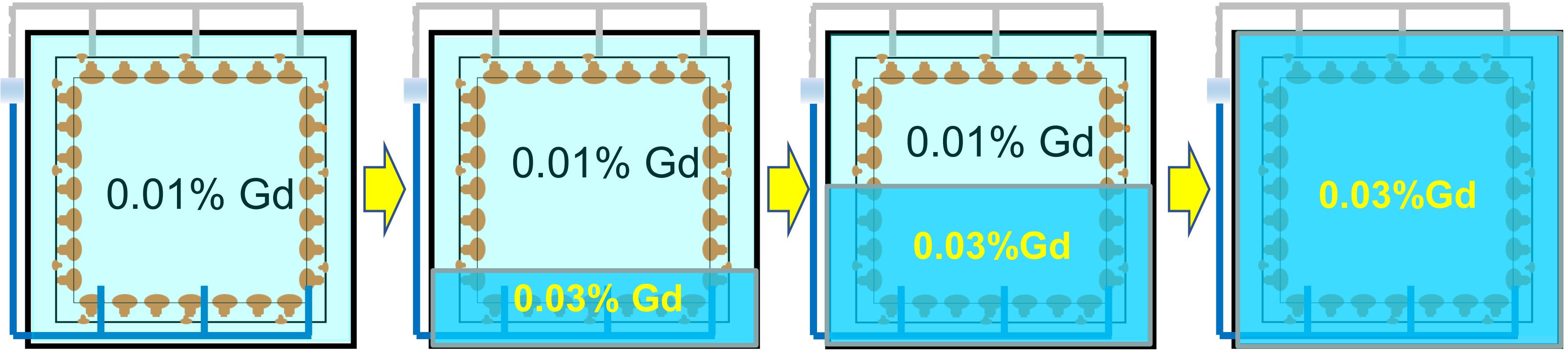
The 2nd Gd-loading Jun 1 – Jul. 5, 2022

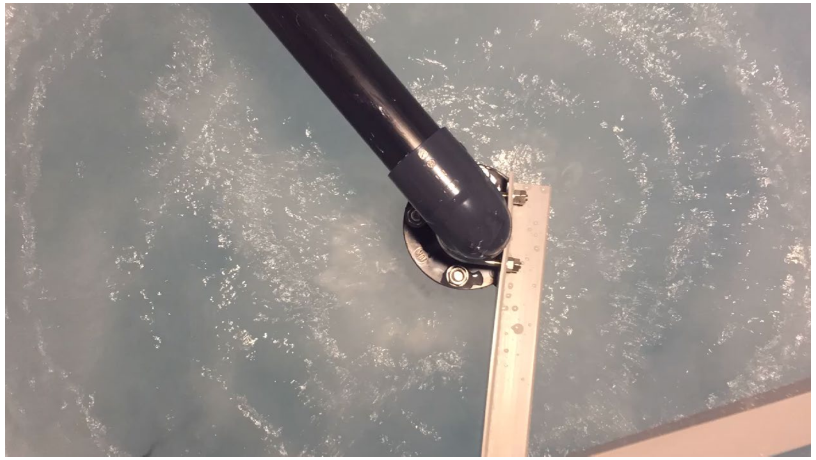
0.01% Gd water was taken from the top and returned from the bottom in **0.06% $Gd_2(SO_4)_3$** solution **(=0.03% Gd = 0.078% $Gd_2(SO_4)_3 \cdot 8H_2O$)**. It took 35 days to replace 50,000 tons of water at 60 m^3/h

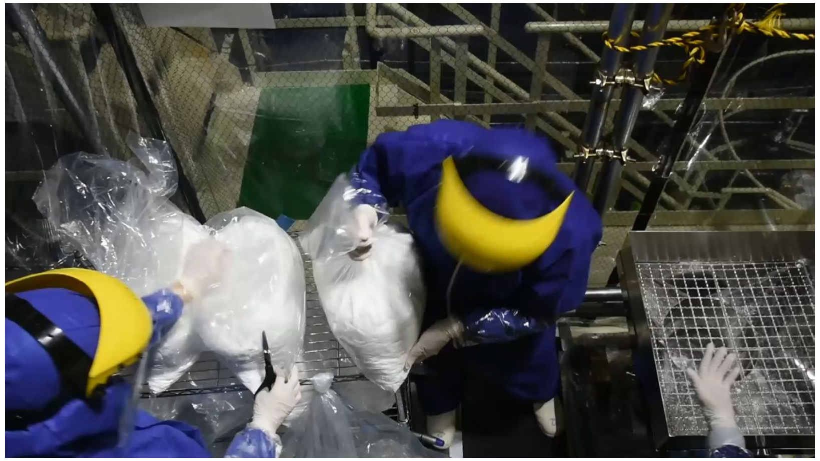
The doubled dissolving capacity

One batch:
17 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$
+ 1600 L of SK water

~900kg /day x 35 day







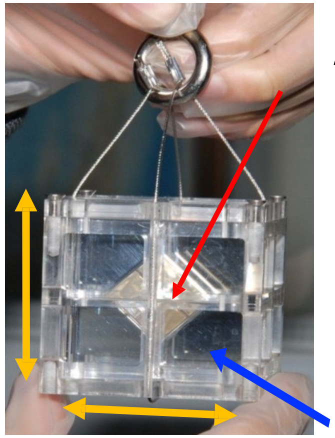
27tons
=1350 x 20kg cardboard boxes!

NIMA 1027 (2022) 166248
NIMA 1065 (2024) 169480

Gd concentration check

- Neutron capture time agrees with the expected value from the amount of loaded Gd

Am/Be neutron source was deployed in SK



8 BGO Crystals

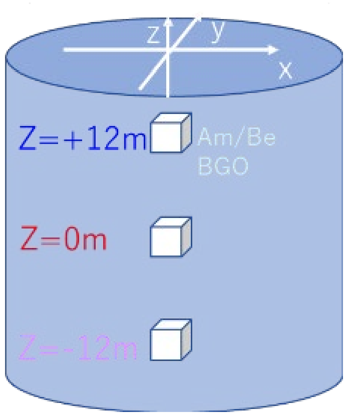
Am/Be neutron source

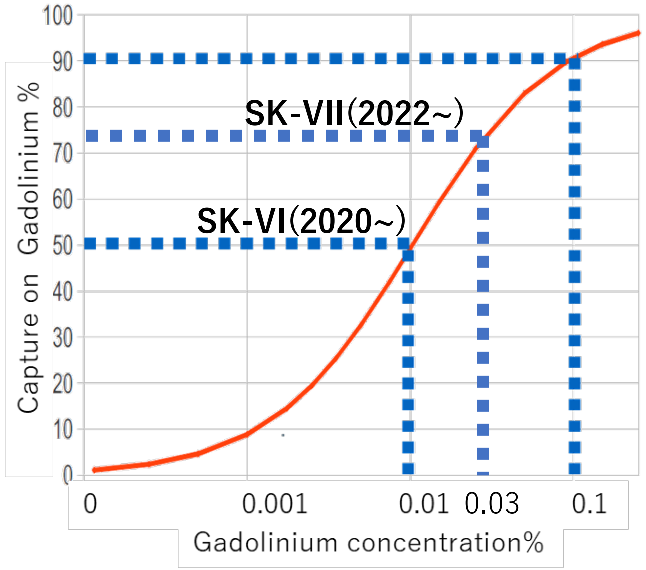
100~200 neutrons/s

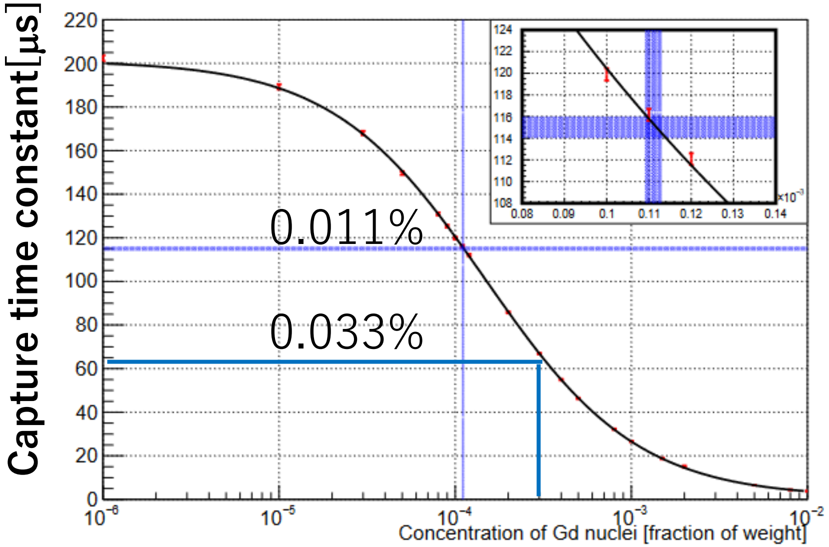
$^{241}Am \rightarrow ^{237}Np + \alpha$

$^{9}Be + \alpha \rightarrow ^{13}C^{*} + n$ (2-6 MeV)

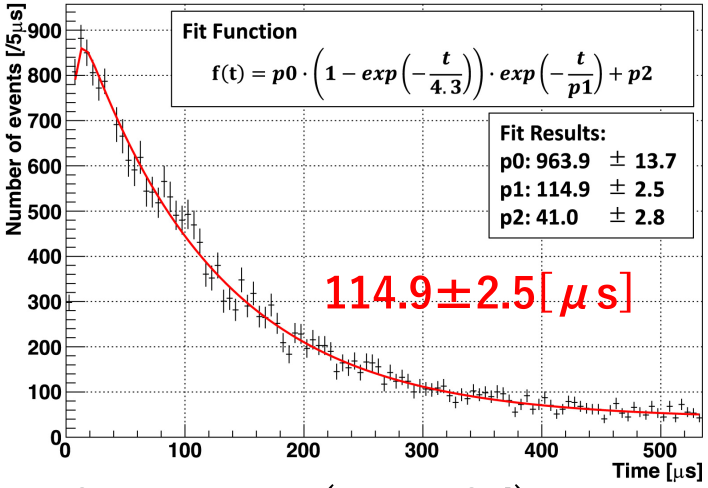
$^{13}C^{*} \rightarrow ^{12}C + \gamma$ (4.43 MeV)



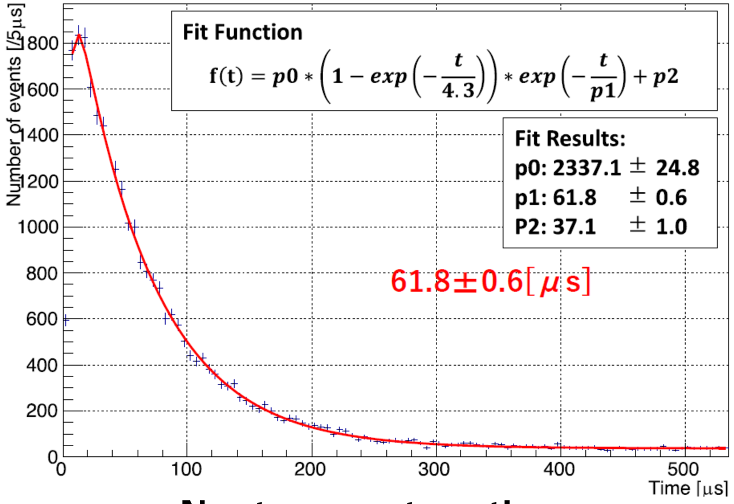




Sep. 29, 2020 (0.01% Gd)



Sep.28 2022(0.03%Gd)

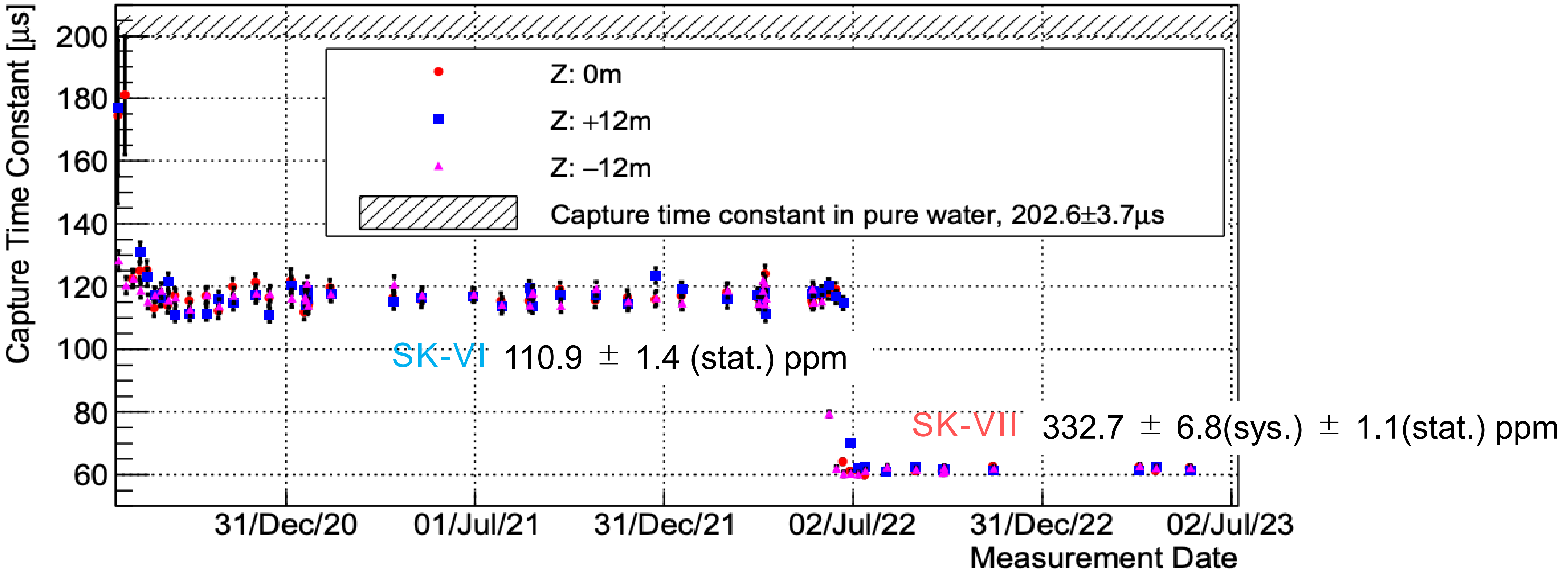


Neutron capture time

NIMA 1065 (2024) 169480

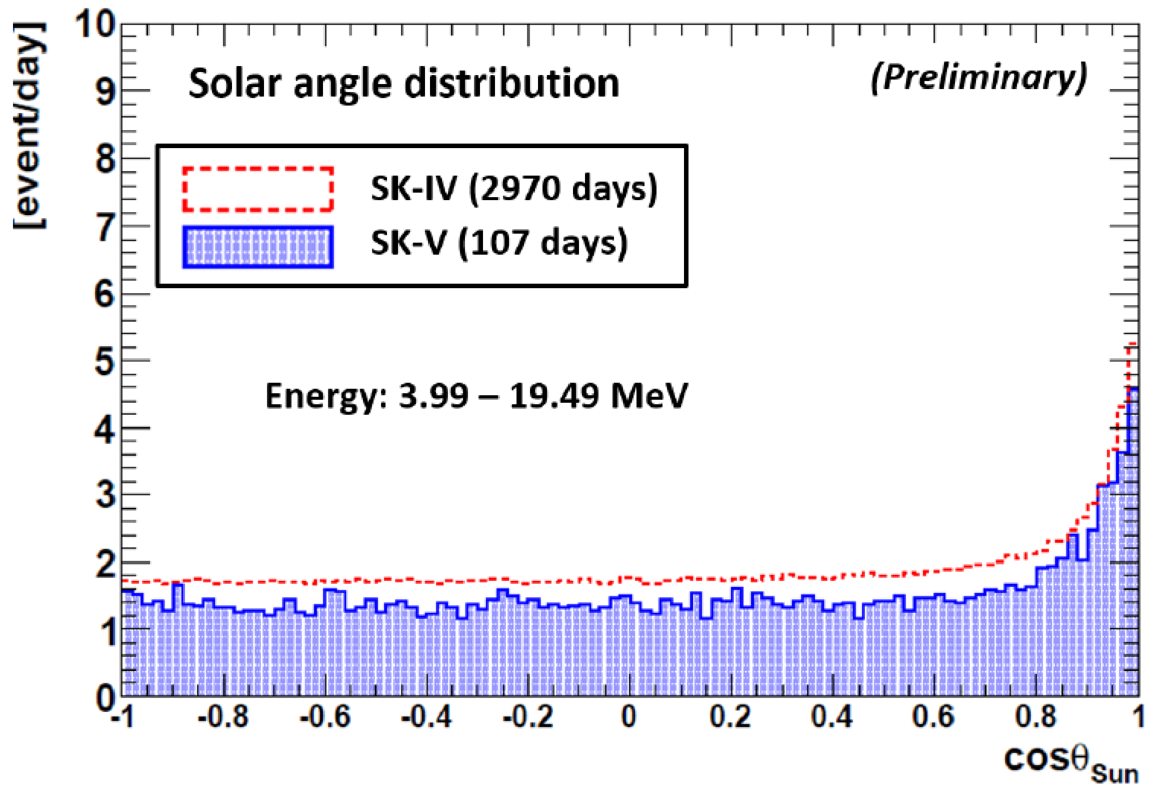
Gd concentration check

- Am/Be calibrations were carried out biweekly
  - **The stability and uniformity are confirmed.**

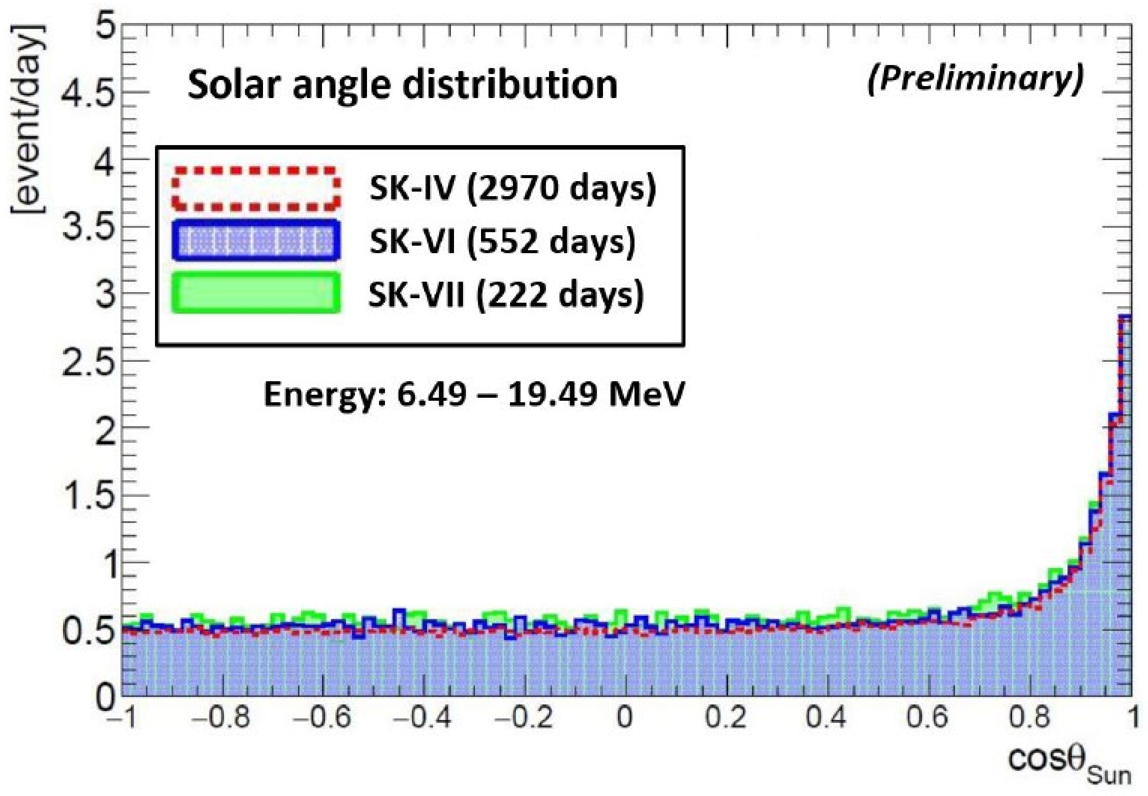


^{8}B neutrinos in SK-V and SK-Gd

- After tank refurbishment



- After Gd loading

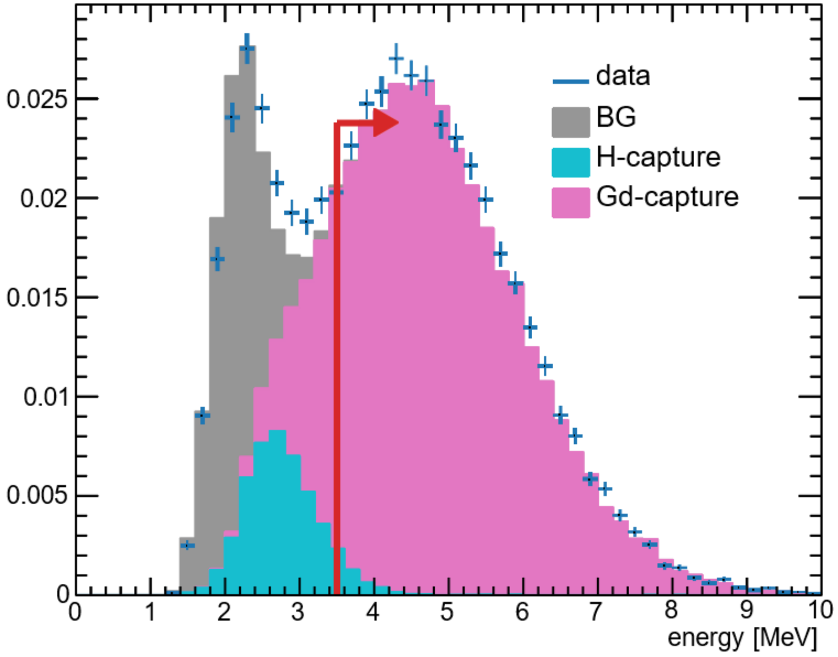


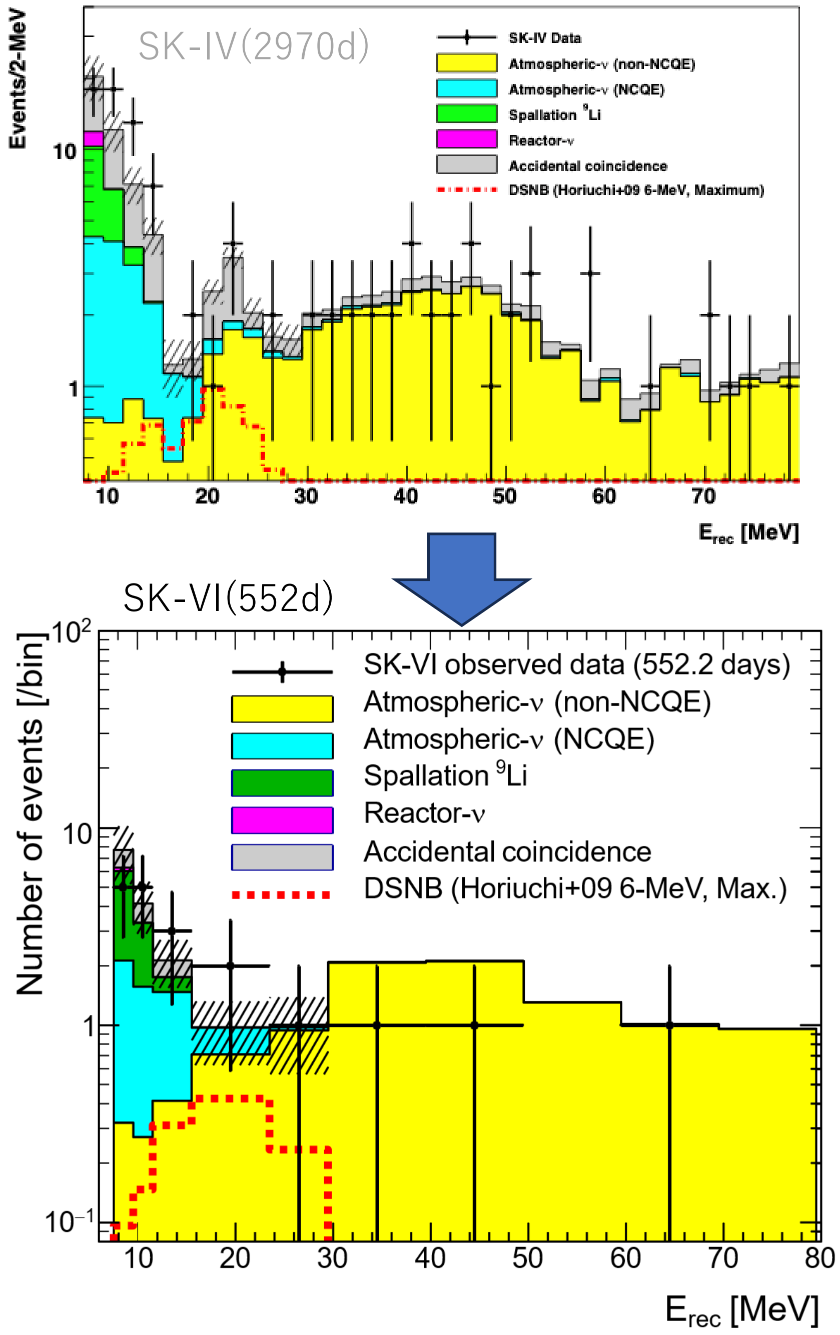
The first result of SK-Gd

ApJ. Letter 951, L27 (2023)

- Using conventional methods with 552 days of data from SK-VI, after the introduction of 0.01% Gd.
- Thanks to Gd, the accidental background was reduced significantly.

Neutron selection in Am/Be calibration



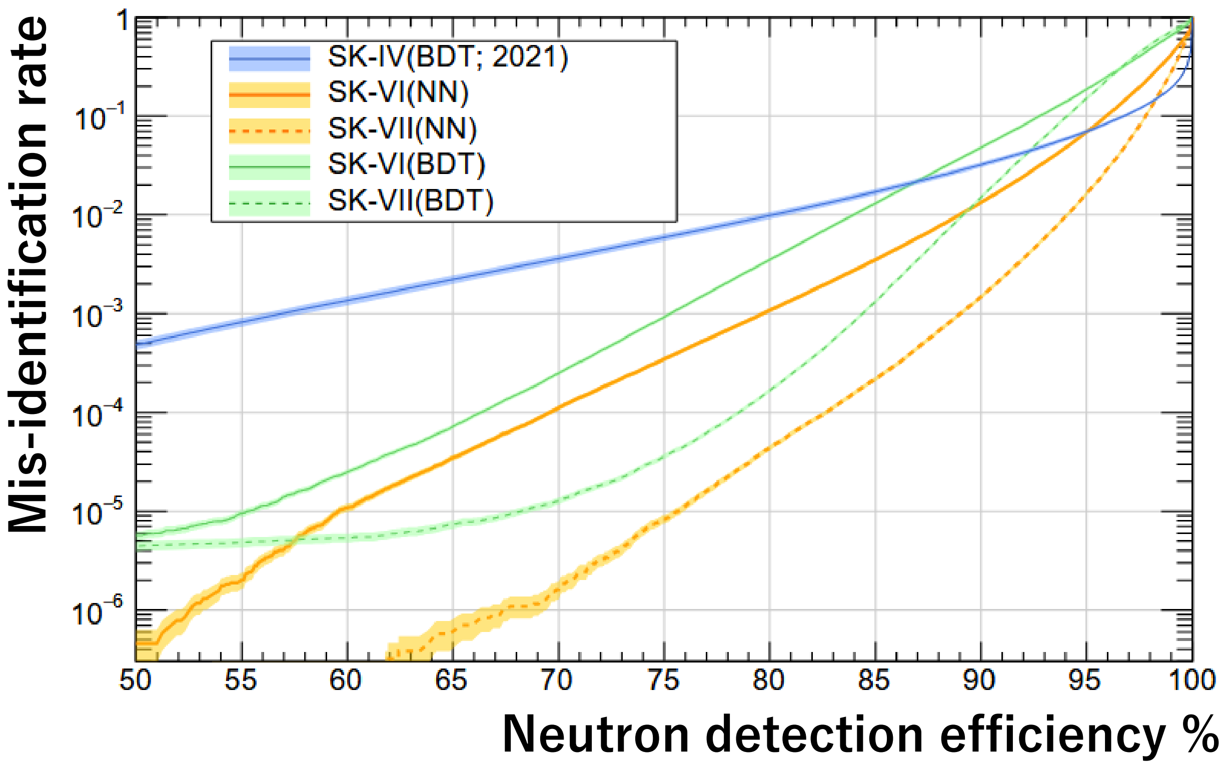


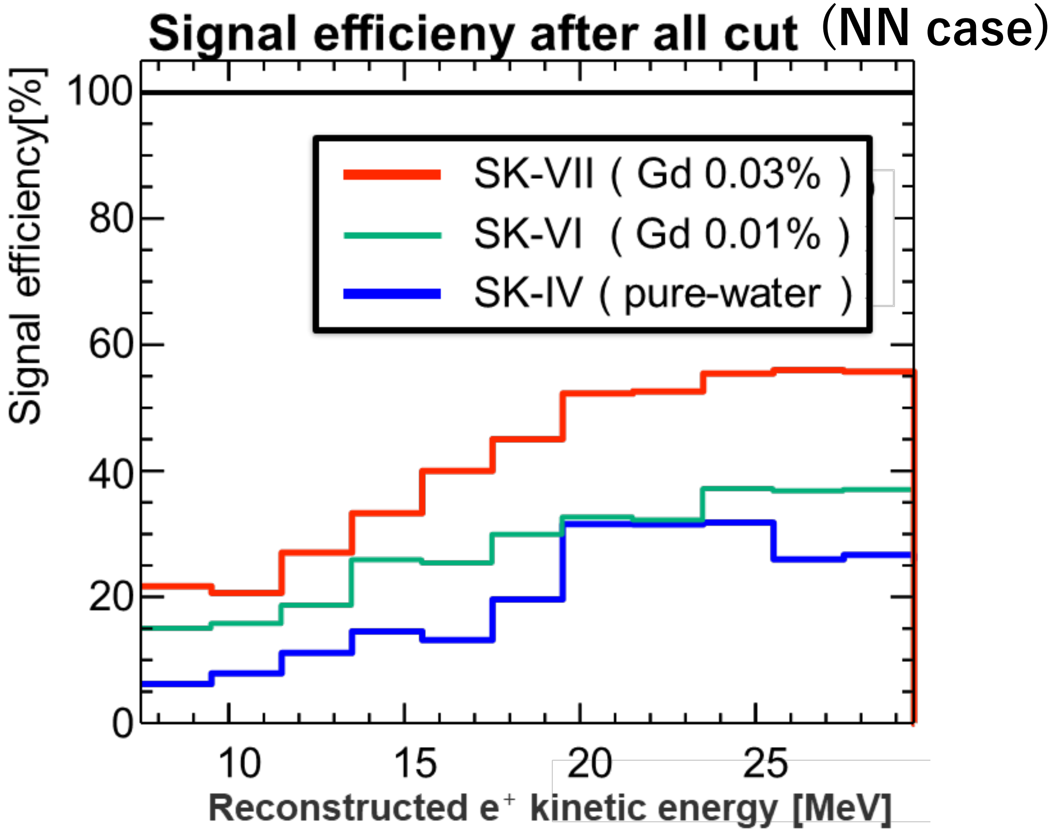
Analysis improvement: ML-based neutron-tagging

Details:
See Rudolph Rogly's Talk

- 2 independent neutron detections
  - Boosted Decision Tree
  - Neural Network

ROC Curve of neutron detection



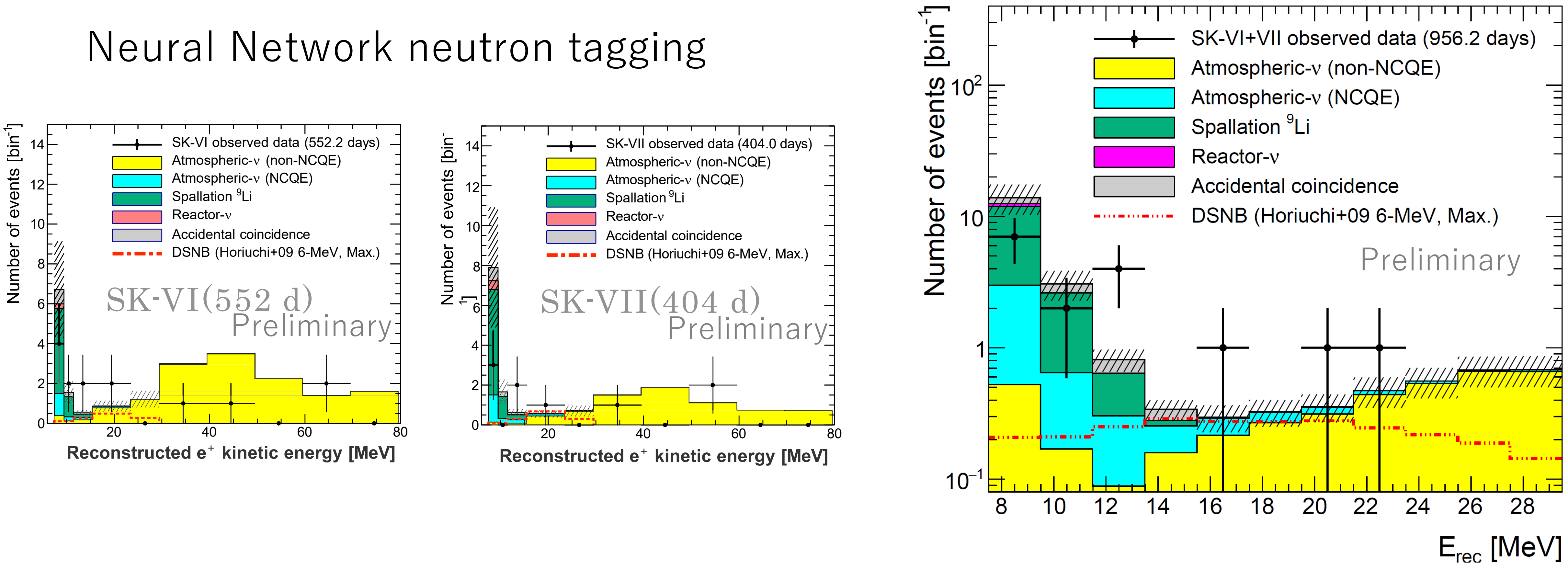


The IBD signal efficiency is significantly improved!

SK-Gd(0.01% 552.2d+0.03% 404d)

Neutrino2024 Harada

Neural Network neutron tagging



- No apparent signal excess, but small indication (minimum p-value = 0.04)

Flux upper limits

- **Spectrum-independent astrophysical $\bar{\nu}_e$ flux limit**
- Stringent limit 10MeV < E

SK-VI+VII 956.2 days, Observed 90% C.L. (This work)

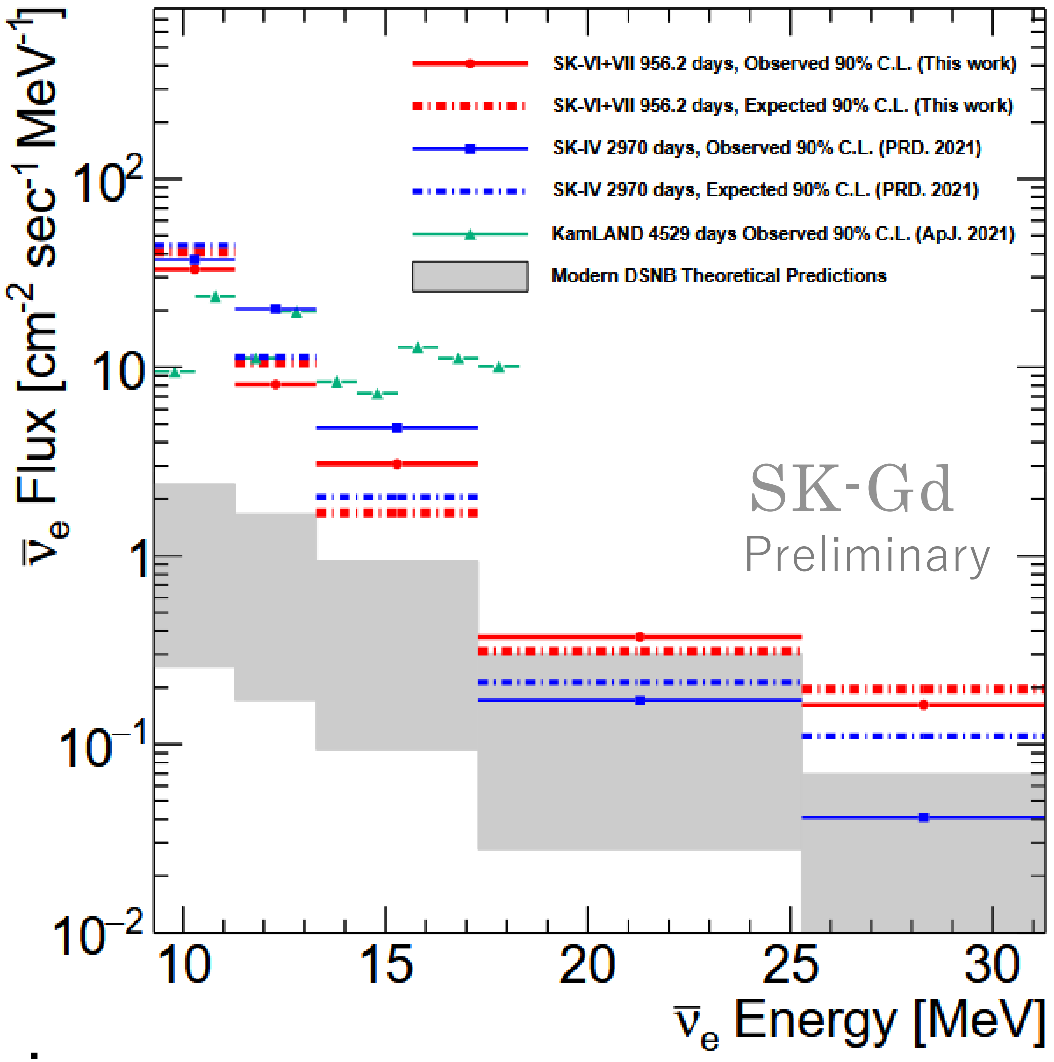
SK-VI+VII 956.2 days, Expected 90% C.L. (This work)

SK-IV 2970 days, Observed 90% C.L. (PRD. 2021)

SK-IV 2970 days, Expected 90% C.L. (PRD. 2021)

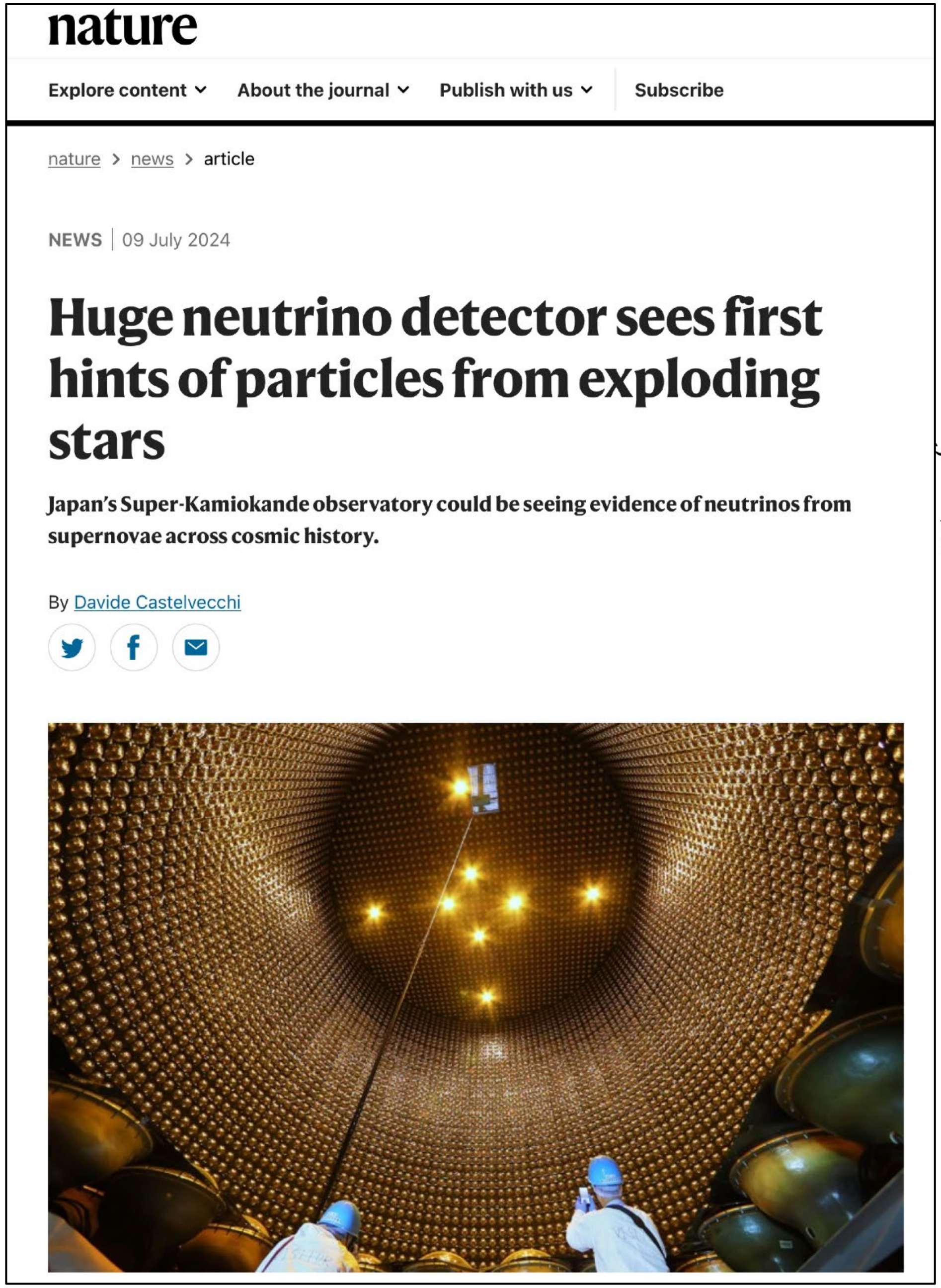
KamLAND 4529 days Observed 90% C.L. (ApJ. 2021)

Modern DSNB Theoretical Predictions



We will soon submit the paper on "SKVI+SKVII" analysis

Combination with pure-water phase:　Hints?


nature

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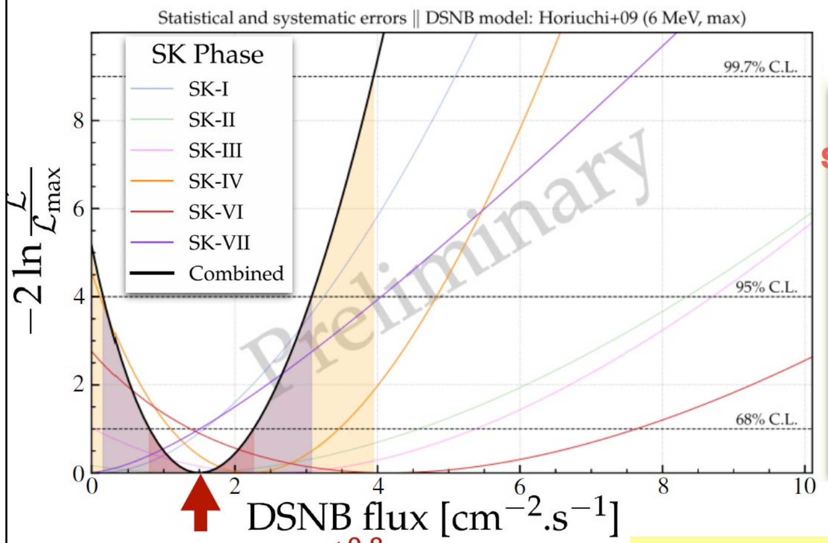
NEWS | 09 July 2024

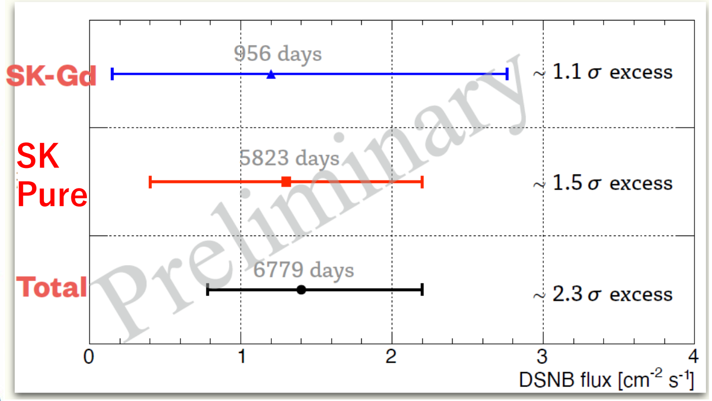
Huge neutrino detector sees first hints of particles from exploding stars

Japan's Super-Kamiokande observatory could be seeing evidence of neutrinos from supernovae across cosmic history.

By Davide Castelvecchi



Best fit: $1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}



Rejecting the zero DSNB hypothesis at 2.3σ

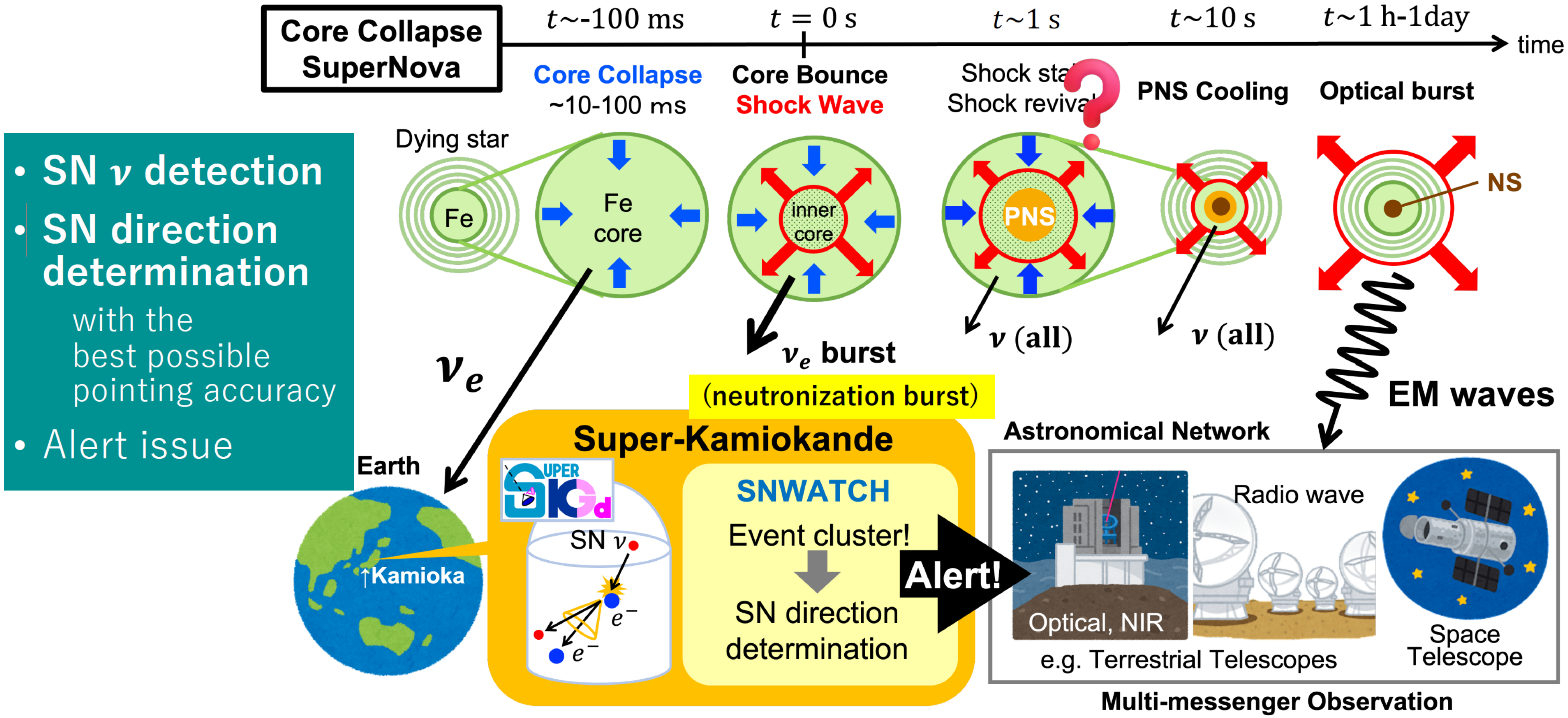
SK 6779 days of data
(5823 days of pure water and 956 days of Gd water)

Aiming for discovery

- Lowering the analysis threshold
- Advancing the understanding of the atmospheric neutrino background through T2K

Multi-messenger astronomy of SNe

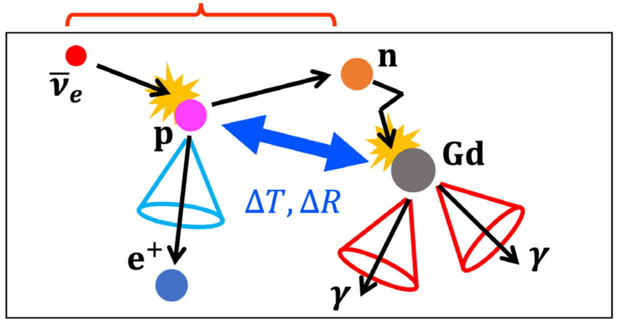
- Coordination with follow-up observation networks following the optical burst and electromagnetic signals.
- **The neutrino burst occurs 1min~1day before the shock break out**



Quick IBD/ES separation for alert

- **Speed-oriented real-time simple IBD tagging algorithm**

prompt candidates

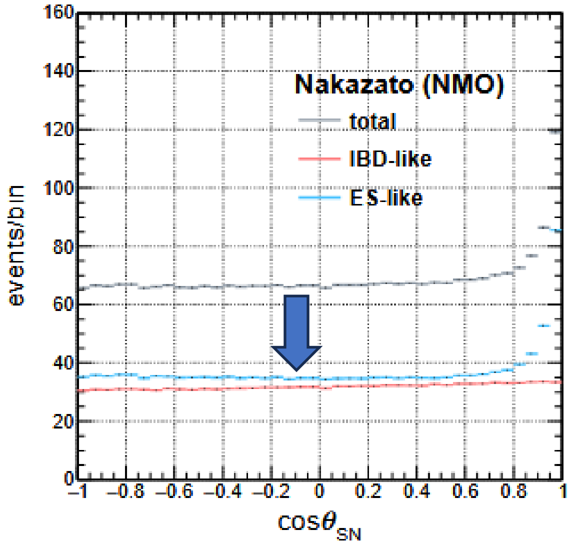


delayed candidates

① Selection of prompt candidates ≧6MeV
② Selection of delayed candidates
③ Neutron tagging pair of events with

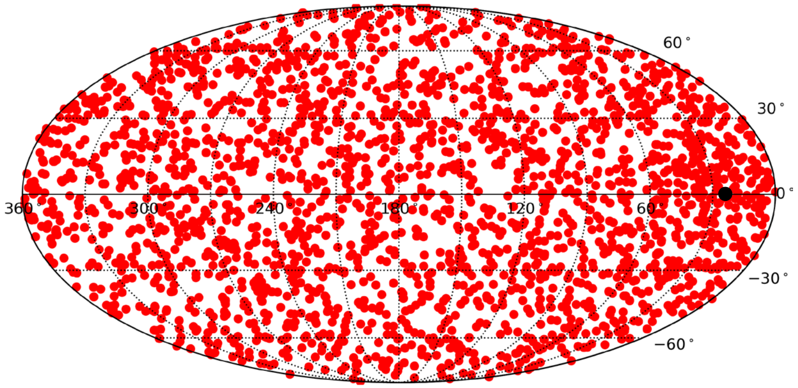
$$\Delta T < 500\ \mu s\ \&\ \Delta R < 300\ \text{cm}$$

This selection algorithm tags ~50% IBD events { **IBD-like**, **ES-like** }

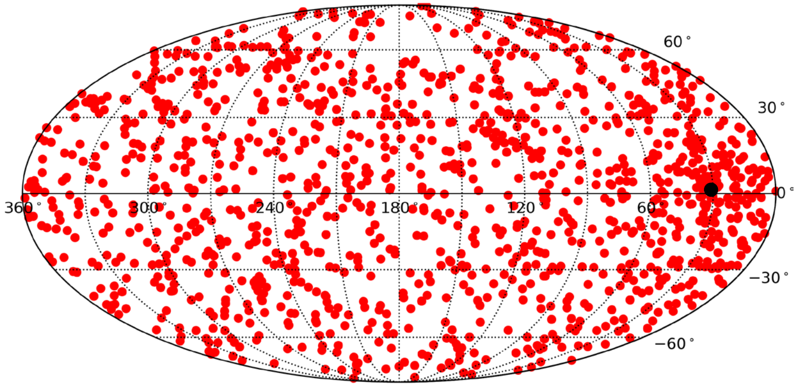


<u>Event direction plot (sky map)</u>

10kpc supernova simulation



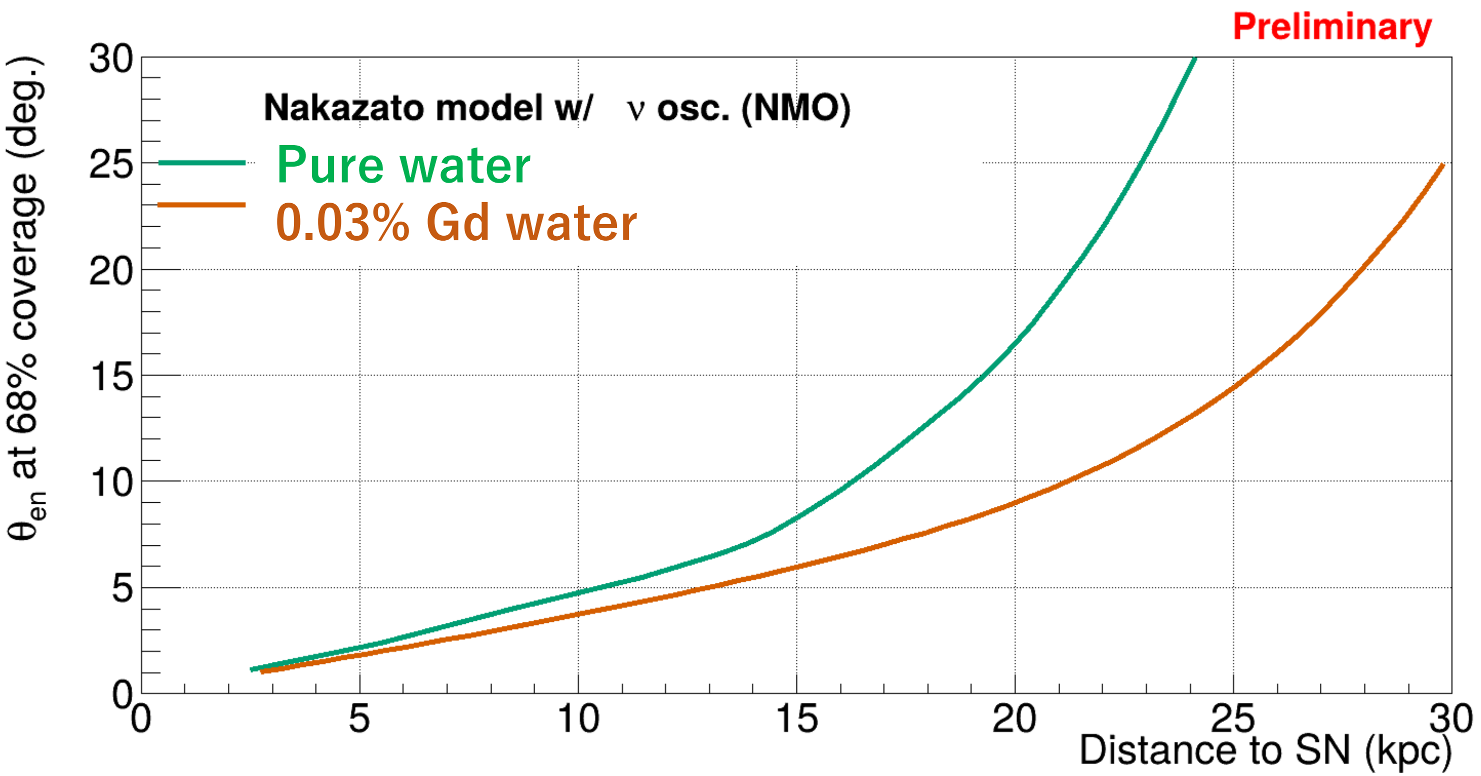
SN burst events w/o IBD tagging



SN burst events w/ 49.7% IBD events tagged/removed

SK's Angular resolution

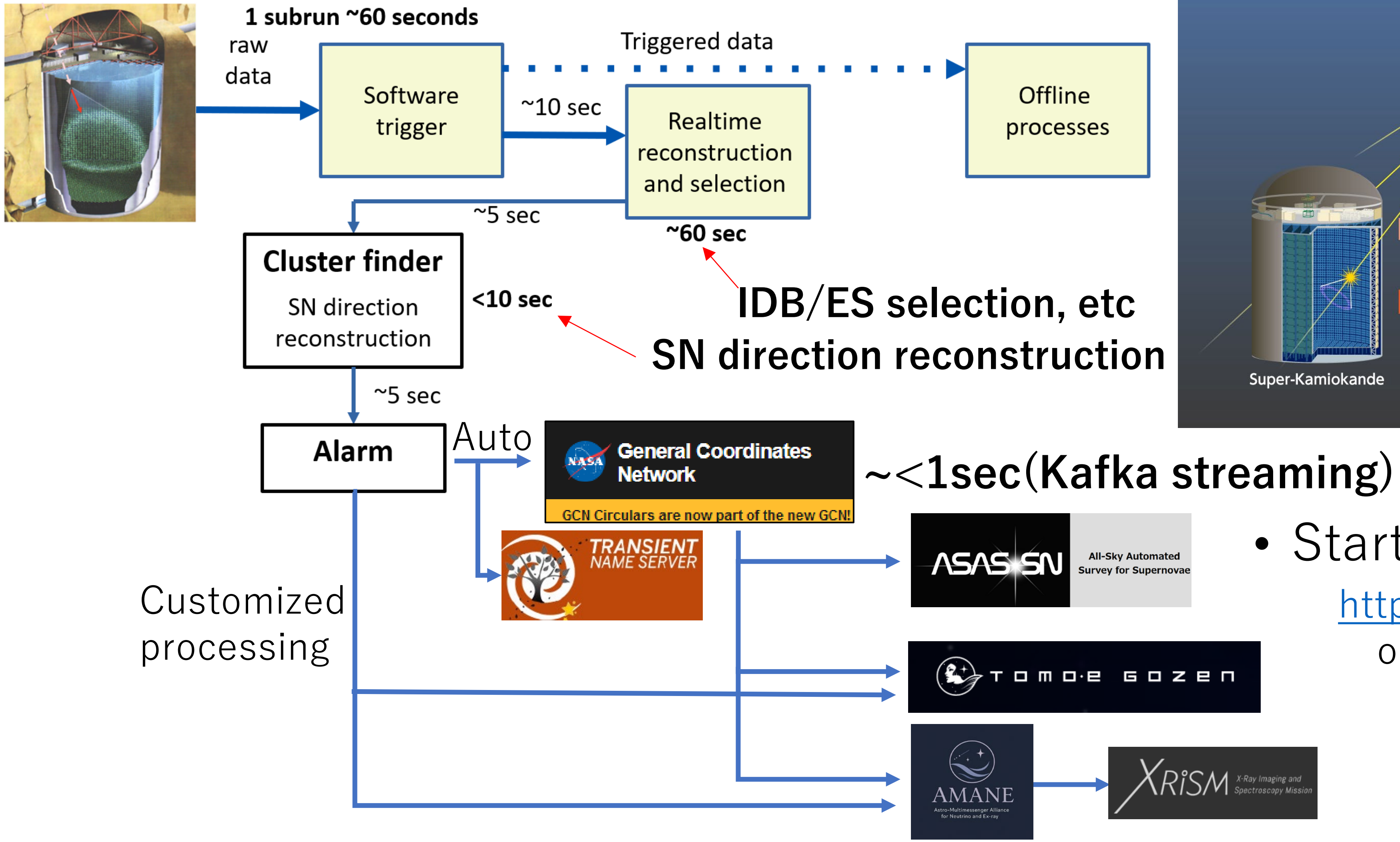
- The current angular resolution of SK

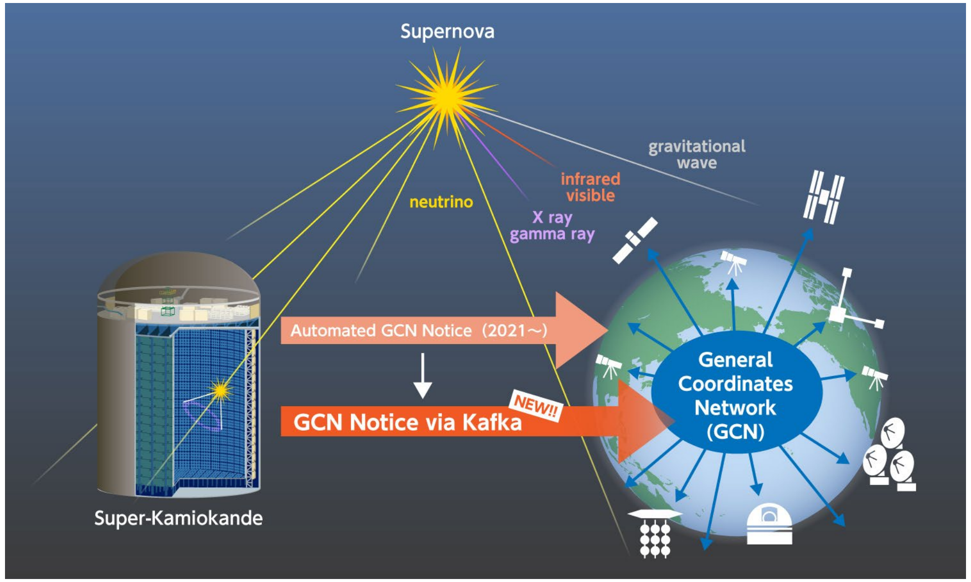


3.68±0.04° at 10 kpc (Nakazato model, 6 MeV threshold)

SNwatch: real-time SN monitor system

- How fast? 10kpc case in 1.5min!





- Starting from Aug 26, 2025

  https://kafka.apache.org/

  open-source streaming platform

Automated Golden alarm to GCN Notice and TNS with direction info.

General Coordinates Network

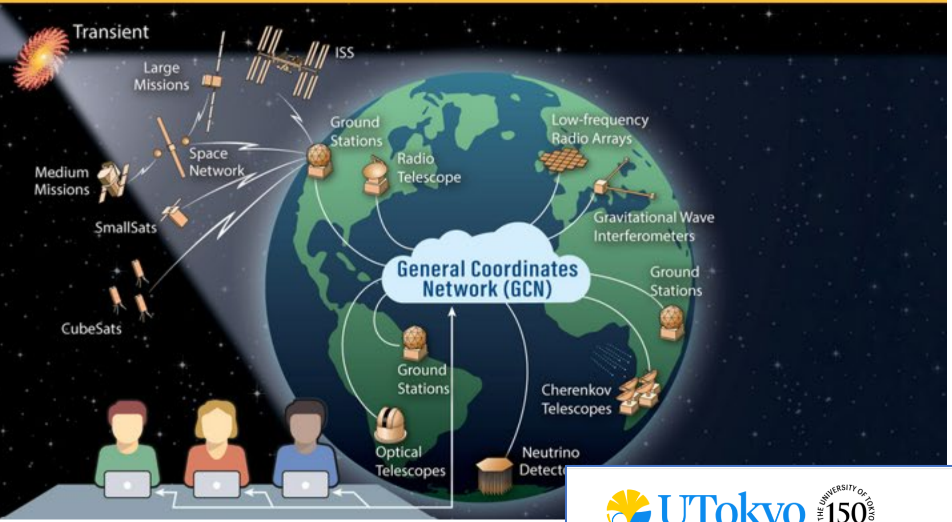
Missions | Notices | Circulars | Documentation | sekiya@icrr.u-tokyo.ac.jp

New! Super-Kamiokande JSON Notices and Schema v4.5.0. See news and announcements

GCN: NASA's Time-Domain and Multimessenger Alert System

GCN distributes alerts between space- and ground-based observatories, physics experiments, and thousands of astronomers around the world.

Start streaming GCN Notices | Post a GCN Circular



GCN News and Events

2025

Aug 26

Super-Kamiokande JSON Notices and Schema v4.5.0

New Super-Kamiokande JSON Notices

The Super-Kamiokande Team and the GCN team are pleased to announce the availability of Su notice types via the new GCN in JSON format. These can be streamed via Kafka. SK remain available via GCN Classic and GCN Classic over Kafka. The information included in the Notices largely overlaps with that in GCN Classic with some additional parameters: the number of detected inverse beta decay (IBD) events, the analysis pipeline used (`snwatch` or `wit`), and the type of processed sample (full or partial) used for event detection.

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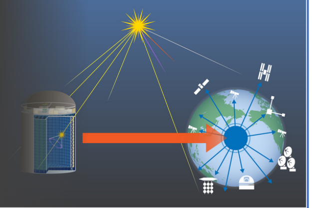
Launch of New Supernova Alerts from Super-Kamiokande



Institute for Cosmic Ray Research

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September 4, 2025

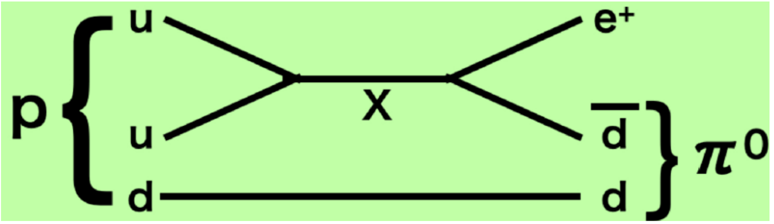
The NASA General Coordinates Network (GCN) and the Super-Kamiokande research team have launched a new system for distributing alerts when Super-Kamiokande detects a "supernova" explosion. Supernovae are the implosions that massive stars undergo at the end of their life cycle. During these cataclysmic events, most of the energy is released in the form of a large flux of neutrinos. Super-Kamiokande can detect this flux if the supernova occurs within the neighborhood of the Milky Way.
With this upgrade, when Super-Kamiokande releases a "supernova alert", the information can be shared with researchers around the world more quickly, in a more user-friendly format, and with richer details.

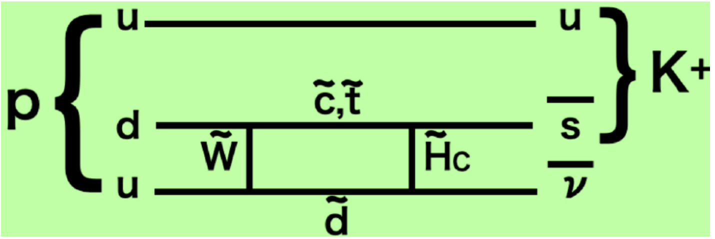
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Recent “non-Gd” SK results

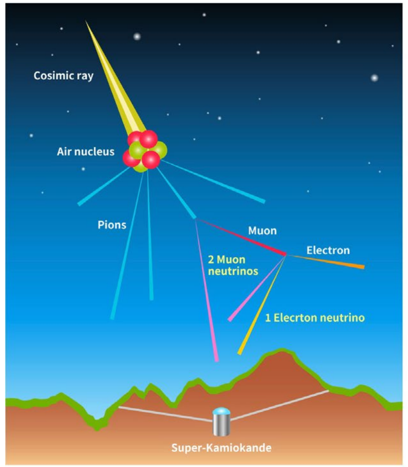
Details are in each physic talks

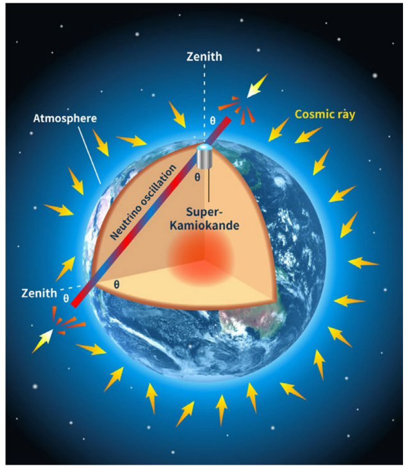
- **Solar neutrino** (Yuuki Nakano)
- **Atmospheric neutrino** (Philipp Eller)
- **Proton decay**(Hide Tanaka)





Atmospheric Neutrinos



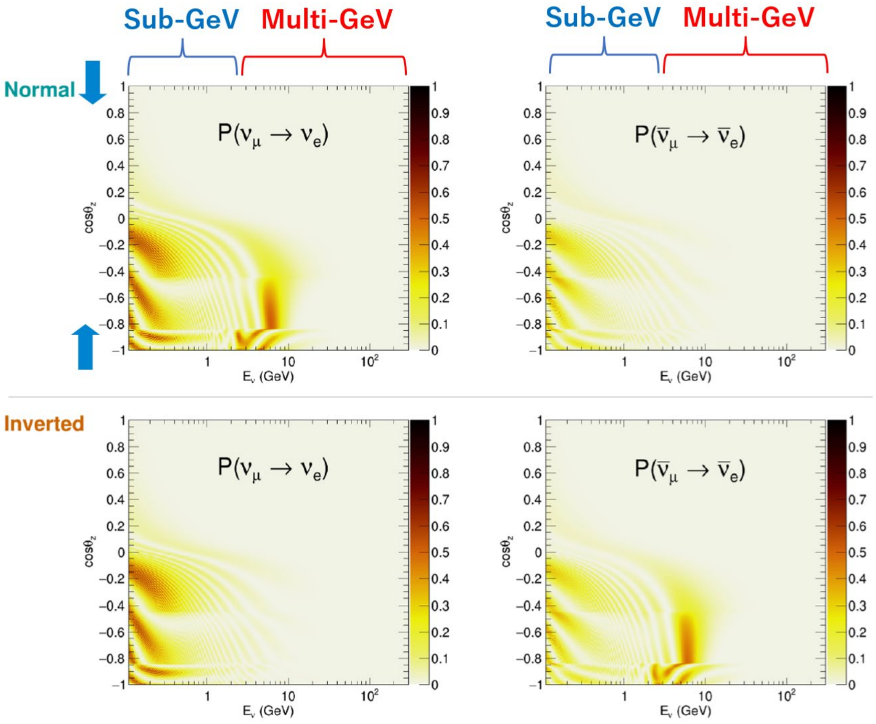


- Cosmic rays interact with air nuclei, and the decay of pions and kaons produces neutrinos

$$P + A \rightarrow N + \pi^{\pm} + X$$
$$\quad \hookrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\qquad \hookrightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

- Neutrinos travel 10 – 10,000 km before detection
- Both ν_μ and ν_e ($\nu_\mu/\nu_e = 2$ at low energy)
- Both neutrinos and anti-neutrinos
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans a wide energy range
  - ~100 MeV – 100TeV

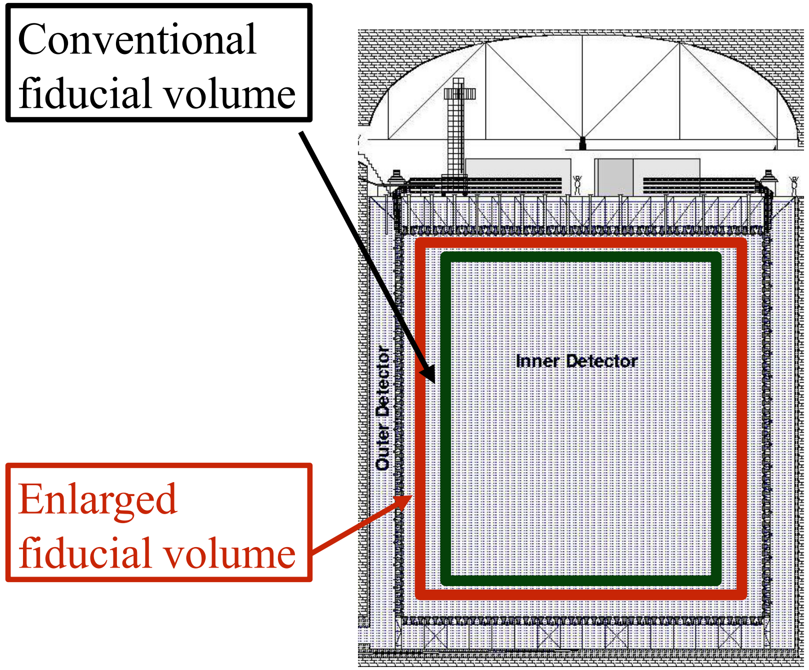
→**Excellent tool for studies of neutrino oscillations**



$\sin^2\theta_{12}$=0.31, $\sin^2\theta_{23}$=0.5, $\sin^2\theta_{13}$=0.025
Δm^2 =7.6x10^{-5} eV^2, Δm^2 =2.5x10^{-3} eV^2
δCP=0.0

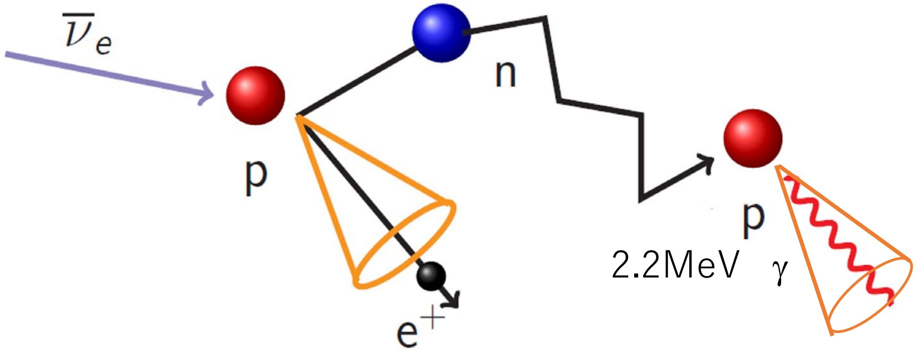
Improvements

- **Enlarged fiducial volume**
  - The fiducial volume was enlarged from 22.5 kton to 27.2 kton and now includes the volume of water between 1 and 2 m from the wall. Corresponding to a ~20% increase in the exposure.

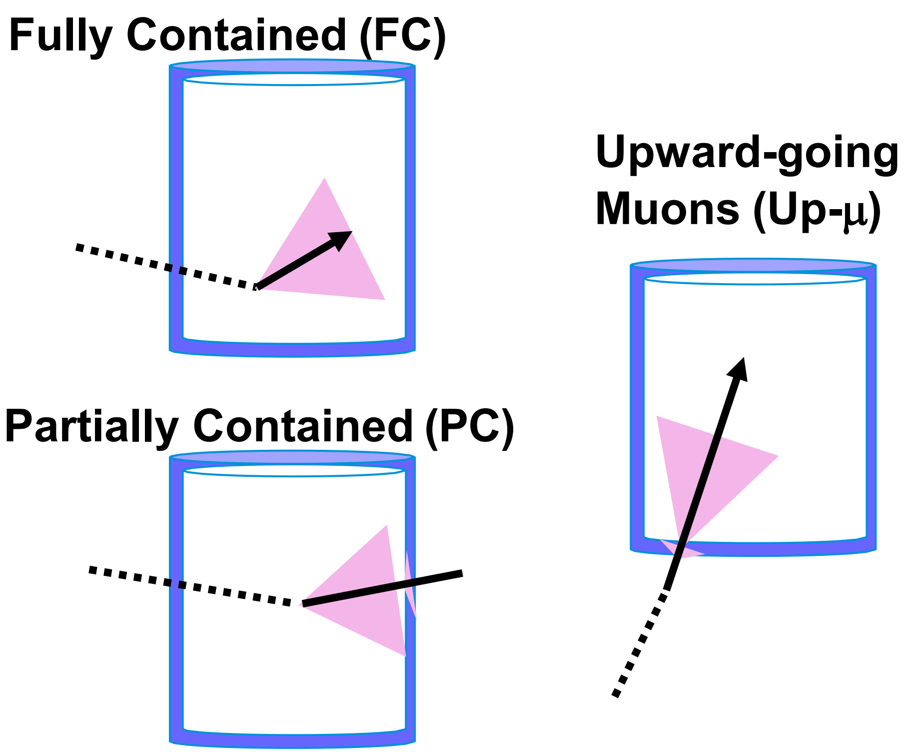


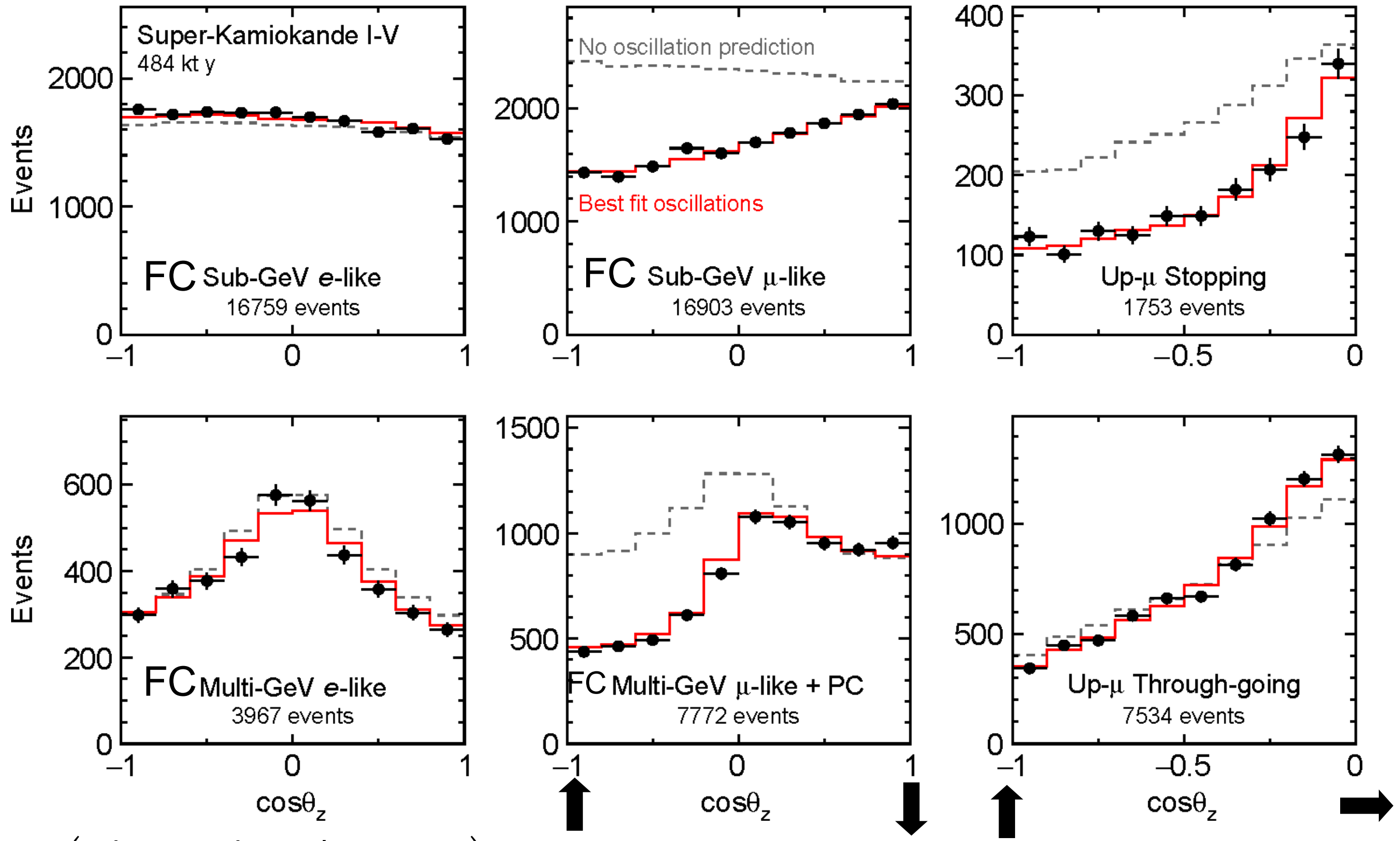
- **Neutron tagging in pure water**
  - Neutron tagging with pure water is adopted in the data of 2008~2020
  - Multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like samples to improve sensitivity for mass hierarchy.

Analyses with more sensitive tagging by Gd are underway.



Atmospheric Neutrino Data



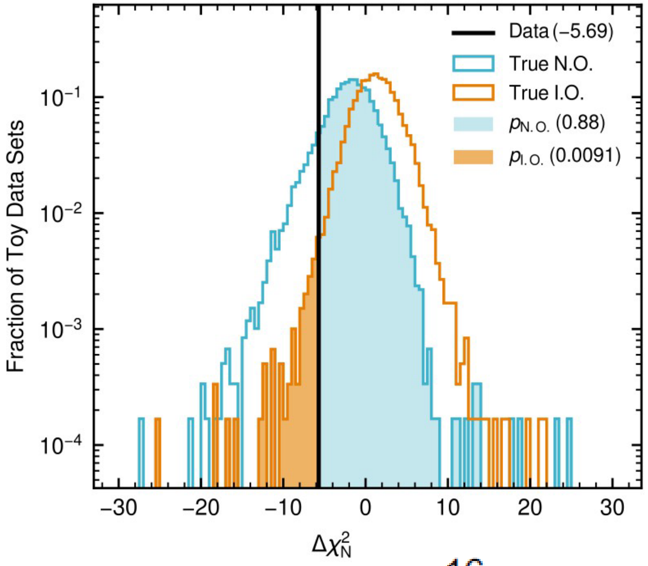


- **6,511 days** of atmospheric neutrino data (Through July 2020)
- **66,002 events** in total (52,628 FC, 4,086 PC, and 9,288 UP-μ)
- **29 analysis samples**: Sub-divided by event topology (FC/PC,UP-μ), energy range, e/μ–like, and # of rings, number of neutron candidates. Multi-GeV e-like samples are divided into **$\boldsymbol{\nu}$-like and $\boldsymbol{\bar{\nu}}$-like samples to improve sensitivity for mass hierarchy.**

484.2 kton-year exposure

Phys. Rev. D 109, 072014

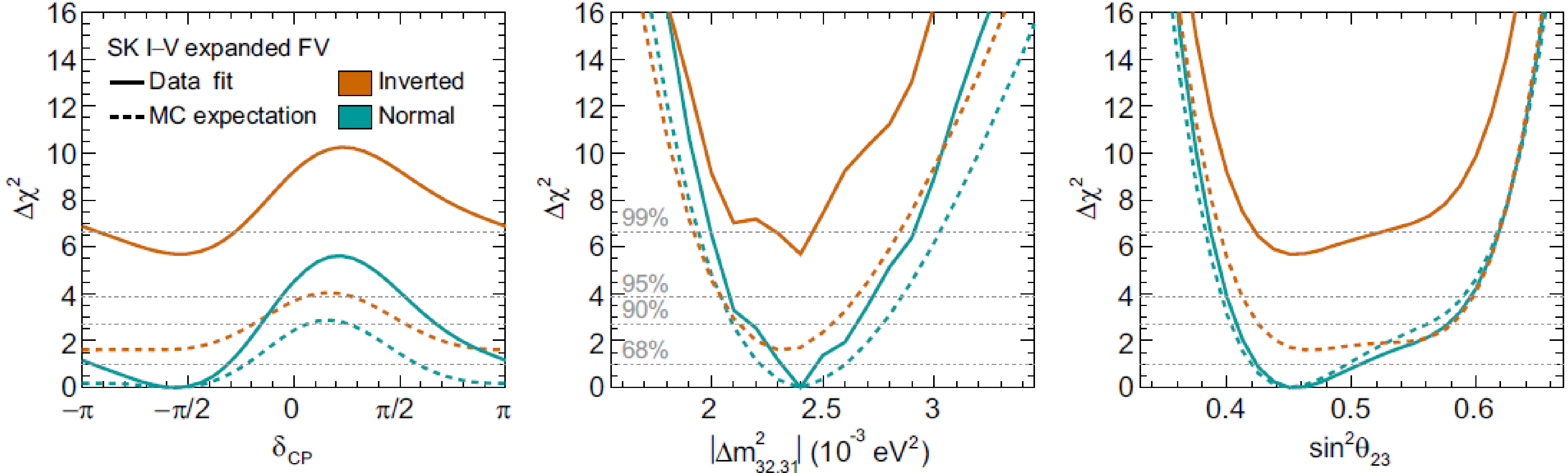
More than 10 times larger than the exposure of the neutrino oscillation discovery analysis!



$\Delta\chi^2 = \chi^2_{NO} - \chi^2_{IO} = -5.69$

The data **disfavor the Inverted Ordering with a significance of 92.3%**

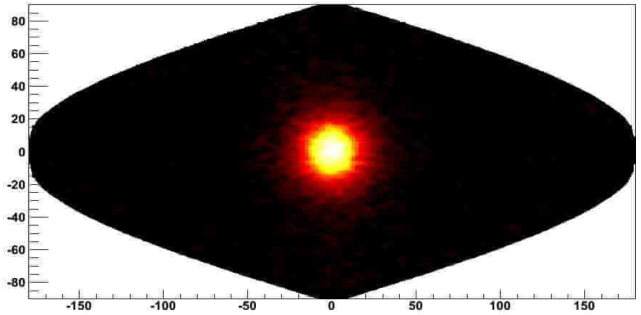
The data **favor $\delta_{CP} \sim -\pi/2$.**



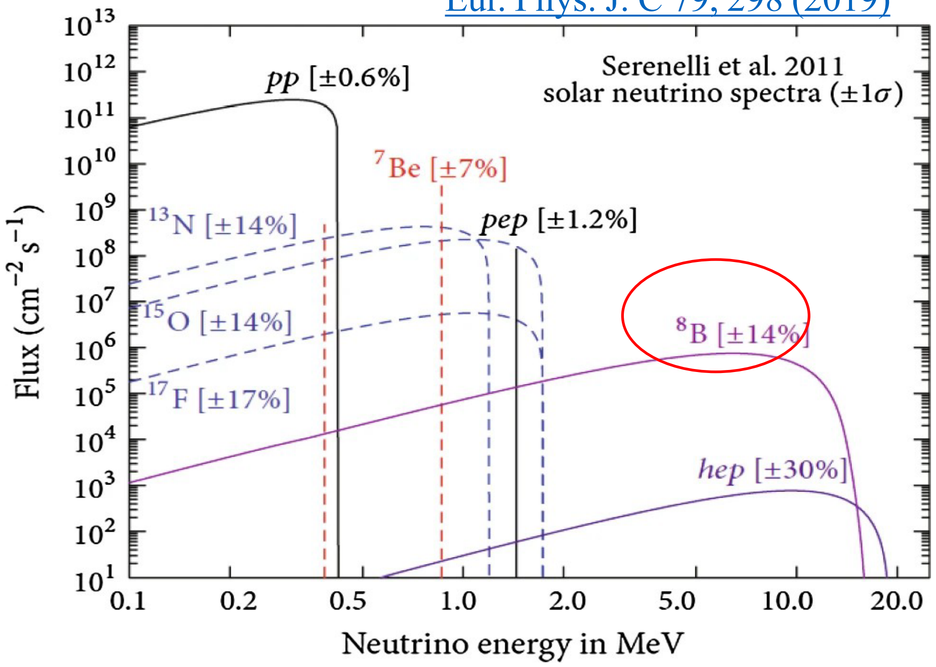
Solar Neutrino

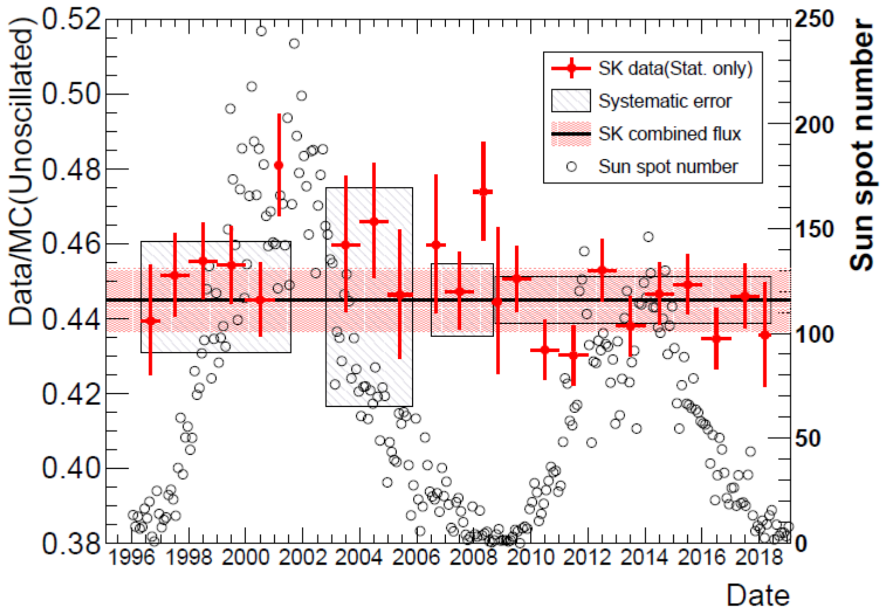
High statistics measurement of ^{8}B solar neutrinos by $\nu_e + e^- \rightarrow \nu_e + e^-$ scattering

Image of the sun by SK



Eur. Phys. J. C 79, 298 (2019)



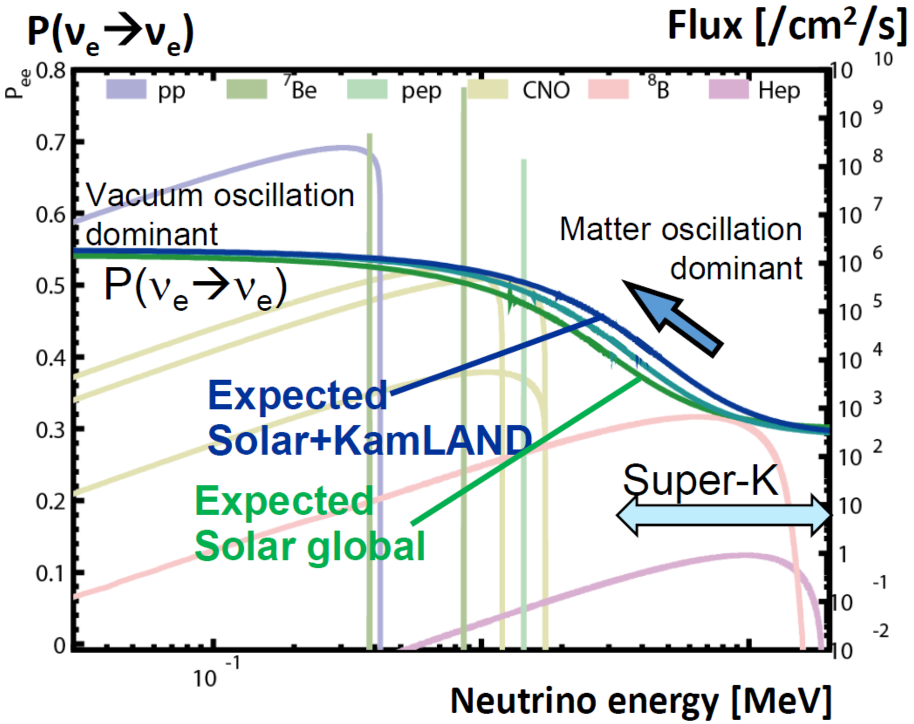


- By April 2024, we analyzed 2970 days of SK-IV data (> **3.5 MeV** kin) from October 2008 to May 2018, bringing the total solar neutrino observation time at SK to **5805 days**.
- No significant correlation between solar neutrino fluxes and sunspot numbers was found during **the 22-year observation period in SK**.

Solar neutrino oscillation

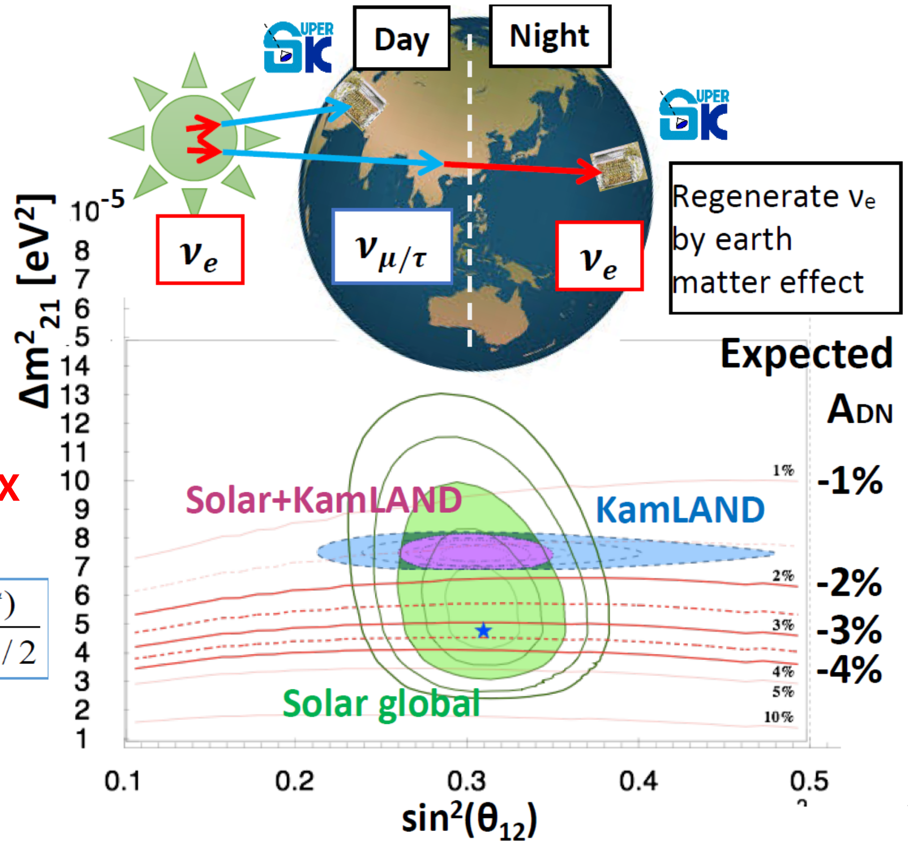
- The ν_e survival probability is influenced by matter effects in both the Sun and the Earth.
  - **Solar matter effect** leads to an energy-dependent **distortion of the ν_e spectrum**.
  - **Earth matter effect** causes a **day–night asymmetry** in the observed flux.
- $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\Delta m_{21}}$ can be constrained through these phenomena.
  - θ_{13} have a small impact on the ν_e survival probability

Spectrum distortion



Day–night flux asymmetry

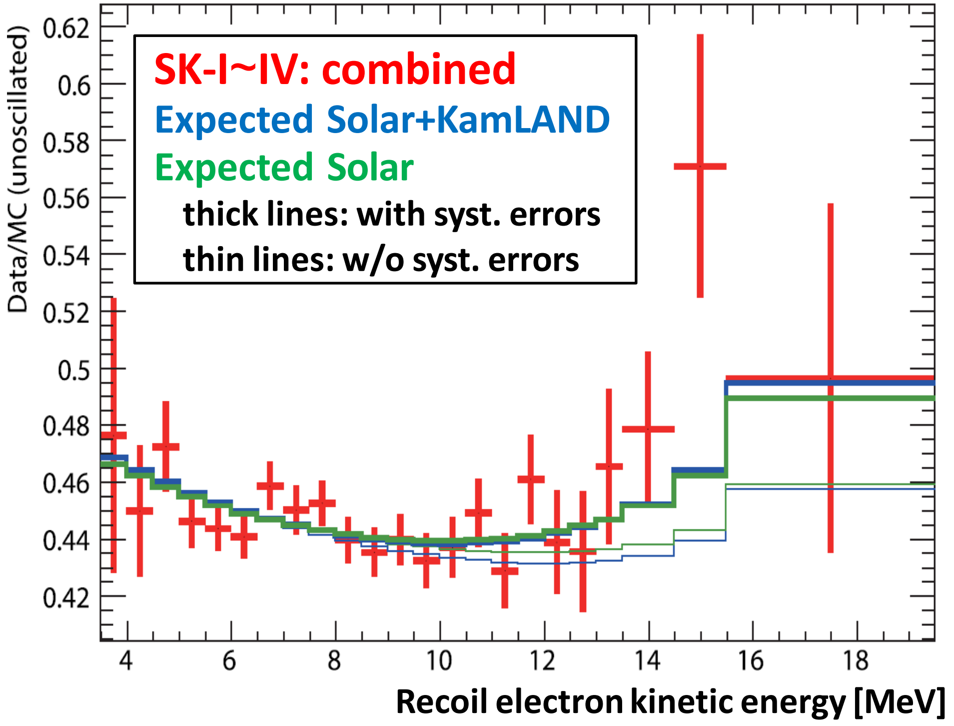
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



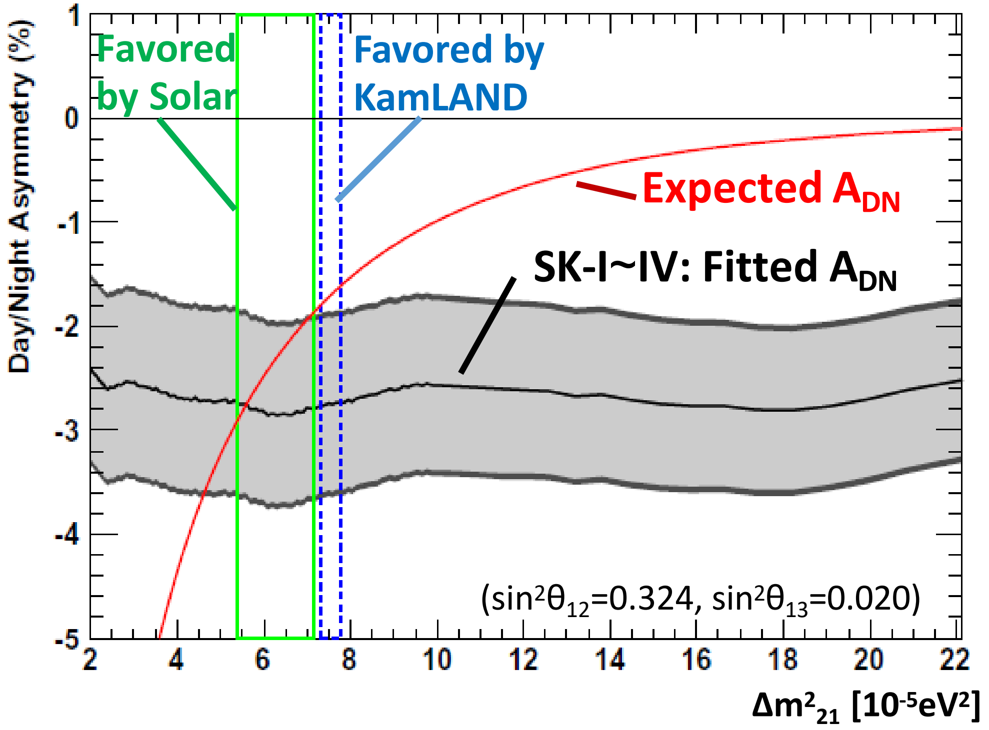
Solar neutrino data

Phys. Rev. D 109, 092001 (2024)

Energy Spectum



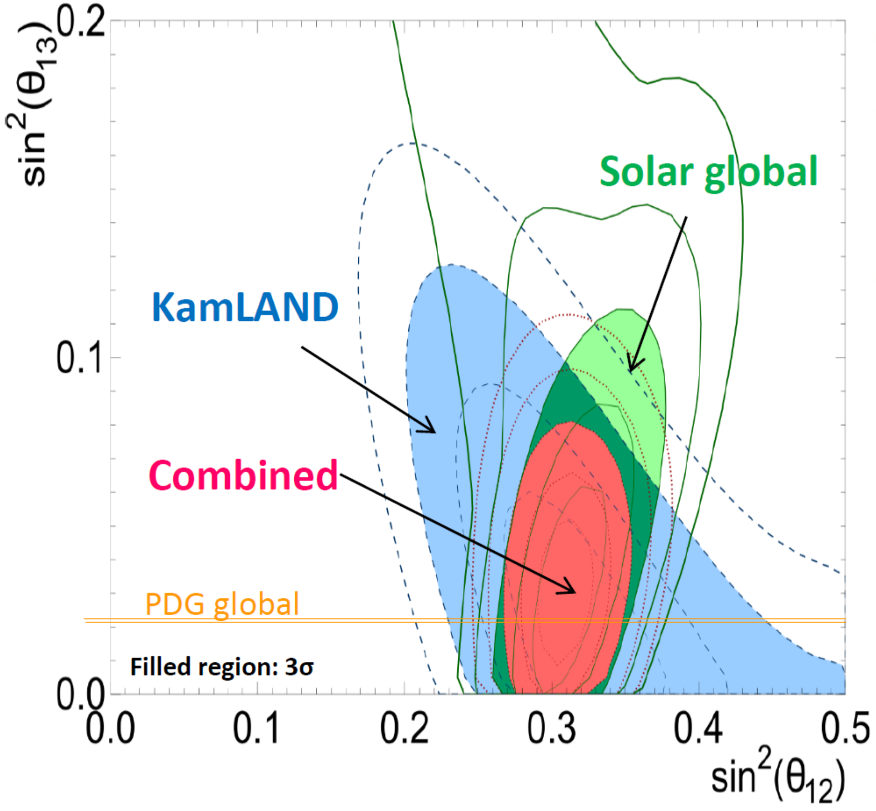
Day/Night asymmetry (A_{DN})

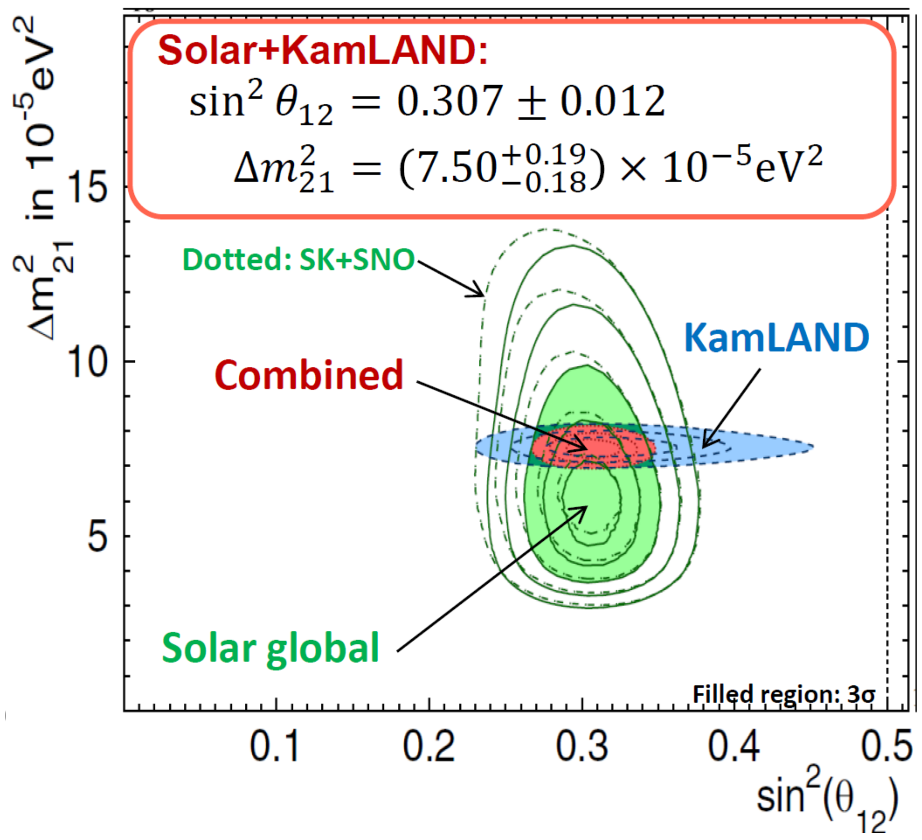


- Flat (i.e. energy independent) $P(\nu_e \rightarrow \nu_e)$ is disfavored with 1.5 σ.
- Fitted A_{DN}(%)=-2.86 $\pm$0.85(stat)$\pm$0.32(syst): 3.2 σ different from 0 ($\sin^2\theta_{12}$=0.324, $\sin^2\theta_{13}$=0.020, and Δm^2_{21}=6.1·10^{-5}eV^2)

Solar neutrino oscillation

Phys. Rev. D 109, 092001 (2024)

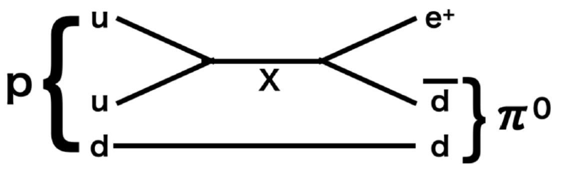




- Finite θ_{13} can be seen with ~2 σ level.
- ~1.5 σ level tension in Δm^2_{21} between Solar global analysis and KamLAND.

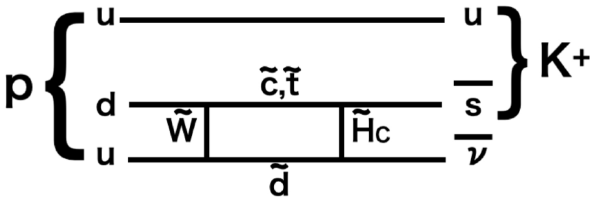
Proton decay searches

- Proton decay is prohibited in the SM, but it is predicted by GUT models. **Observation of proton decay can be strong evidence of GUT**.



$p \to e^+\pi^0$

Dominant in non-SUSY models

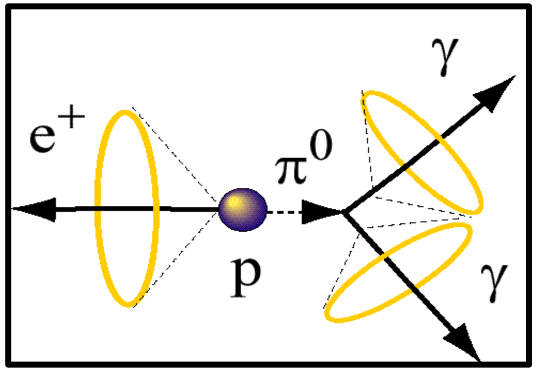


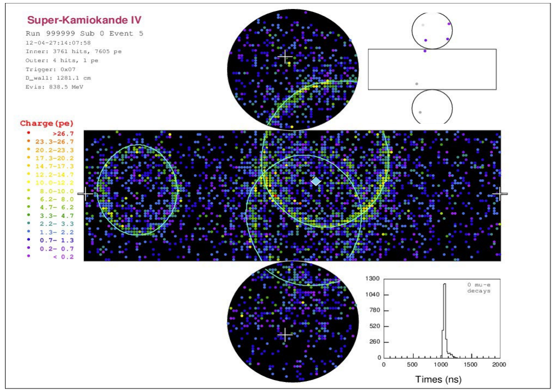
$p \to \bar{\nu}K^+$

Dominant in SUSY models

- In case of the proton decay into **one charged lepton and one neutral pion**($p \to e^+\pi^0$, $p \to \mu^+\pi^0$), **all particles in the final state are visible with Super-K**

  →Able to reconstruct proton mass and momentum





$85 < M_{\pi 0} < 185$ MeV/c^2

$800 < M_p < 1050$ MeV/c^2

$100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c

Improvements

- Expanded FV
  - dwall >200 cm → > 100 cm)
- Neutron-tagging (SK-IV)
  - Further reduce BG by ~50%

Analyzed 450 kton・yrs of data

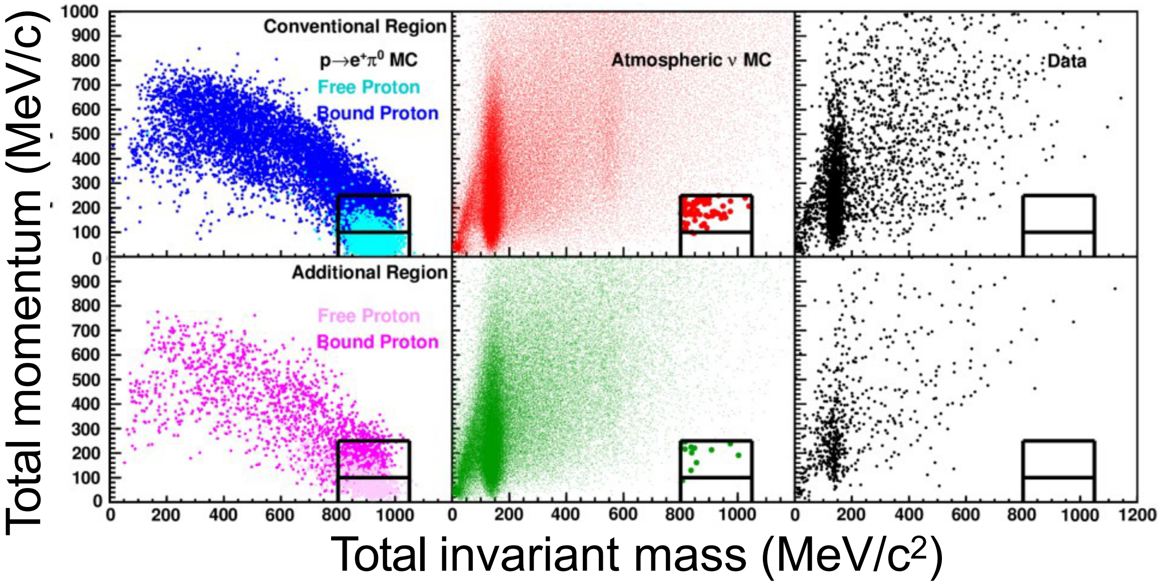
Total mass vs Total momentum

Lifetime limt
(90% CL,450 kton・yrs data)

$p \rightarrow e^{+}\pi^{0}$

Conventional FV
(D_{wall} > 2m)

Additional FV
(D_{wall} =1~2m,
~ 20 % increase)



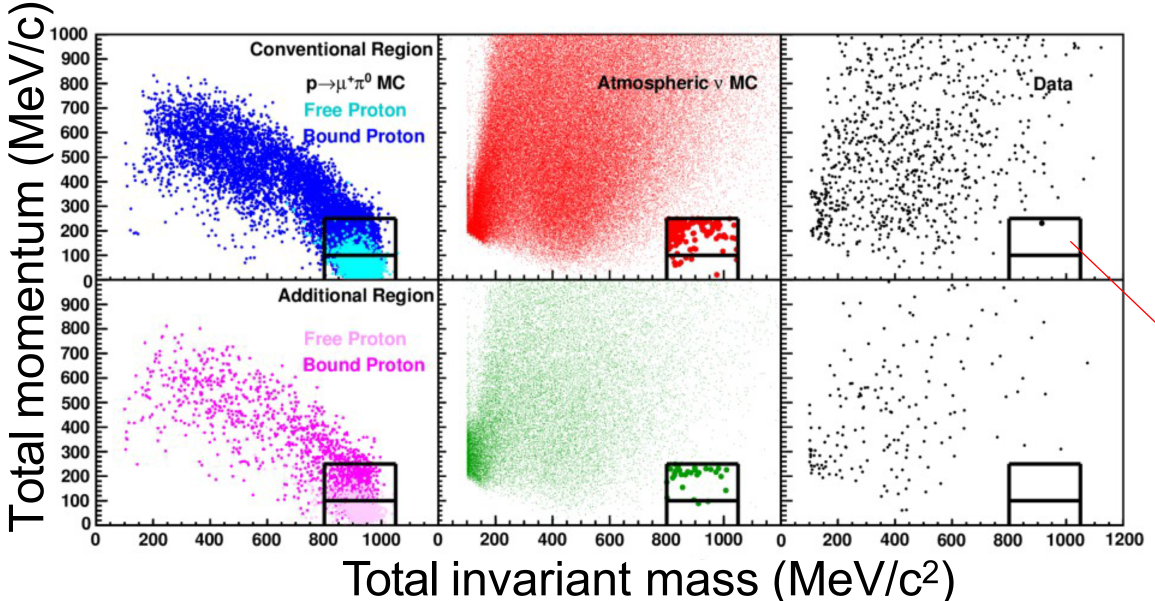
$\tau/Br > 2.4 \times 10^{34}$ years

Exceeded the original goals written in the SK proposal!

$p \rightarrow \mu^{+}\pi^{0}$

Conventional FV
(D_{wall} > 2m)

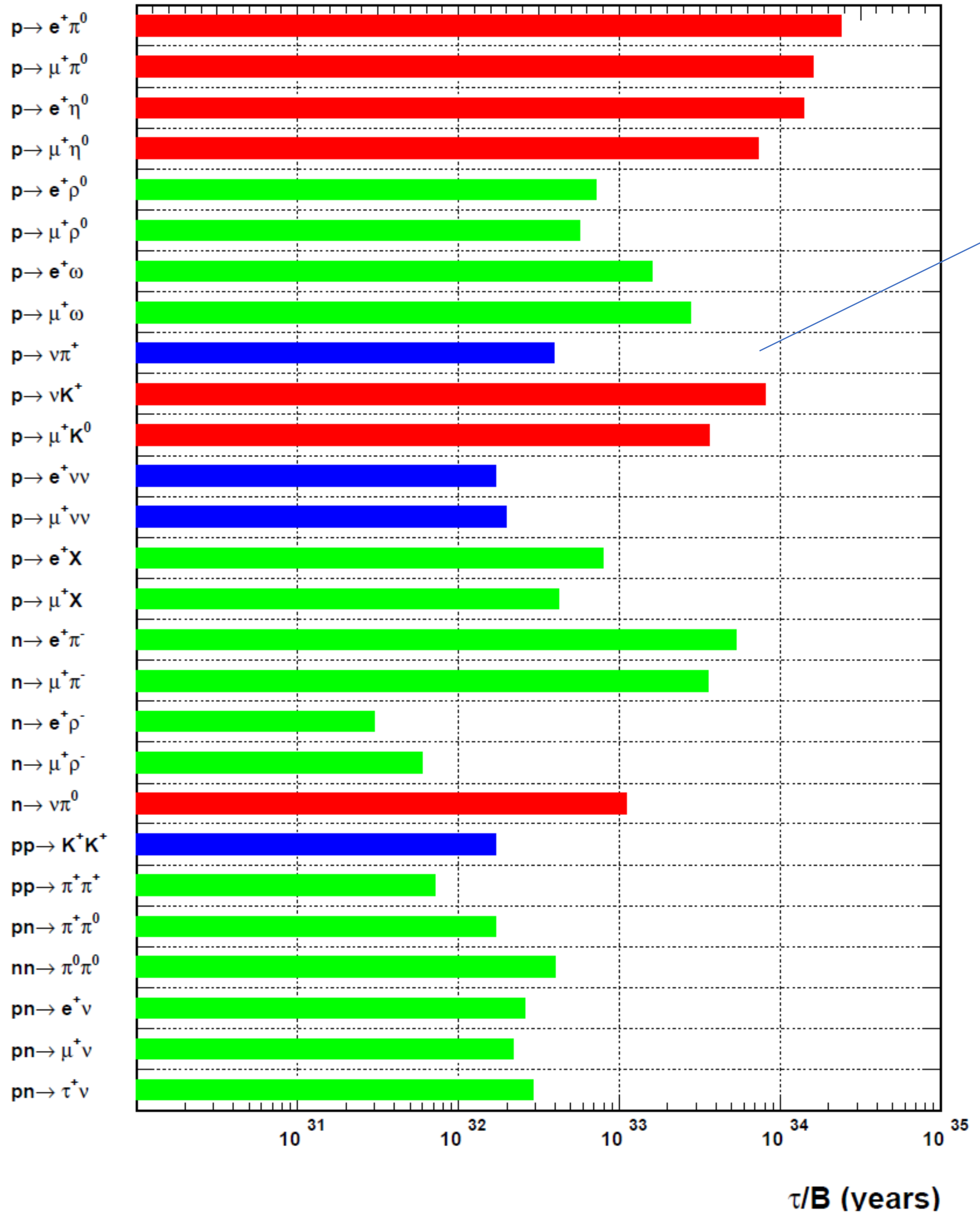
Additional FV
(D_{wall} =1~2m,
~ 20 % increase)



$\tau/Br > 1.6 \times 10^{34}$ years

One event observed.
(expected BG: 0.94 evens)

Nucleon decay limits for various decay modes



$p \to \bar{\nu} K^+$ (365kt・yrs)

$\tau/Br > 8.2 \times 10^{33}$ years

- Reached around 10^{34} years for favored decay modes.
- Searched systematically also for the other modes and reached 10^{32} - 10^{34} years.
- **Stringent limits in the world.**

Red: analyzed with > 365kt・yrs data
Green: analyzed with 350kt・yrs data
Blue: analyzed with SK I-III (173kt・yrs)

Summary

- Since its start in 1996, Super-Kamiokande (SK) has been at the forefront of neutrino oscillations studies, as well as astrophysical neutrino studies and proton decay searches.
- In 2020, SK was upgraded with Gd-loaded water, achieving 75% neutron capture efficiency at a 0.03% Gd concentration.
- With this upgrade, the DSNB search has advanced, maintaining the world’s leading sensitivity.
- SK plays a unique role in multi-messenger astronomy by providing early, directional neutrino alerts that trigger optical and X-ray follow-ups.
- Ongoing Gd-based analyses include studies of neutrino oscillations and proton decay, with new physics results expected in the near future.
- **The role of Super-Kamiokande remains vital**.