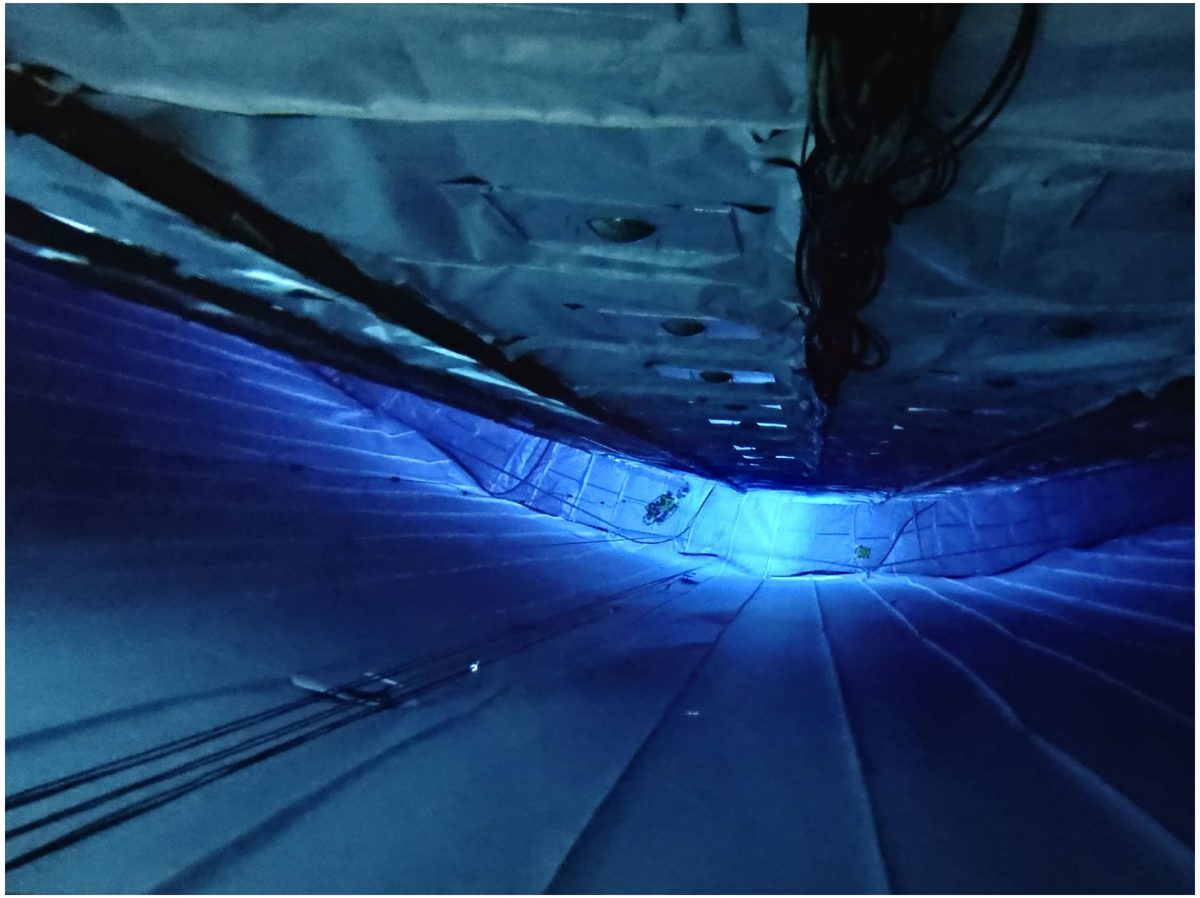
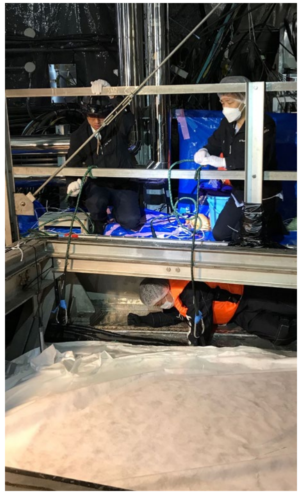






The SK-Gd Journey Toward DSNB Detection

Hiroyuki Sekiya

The Gdfather is reborn (Mark's 60th birthday)

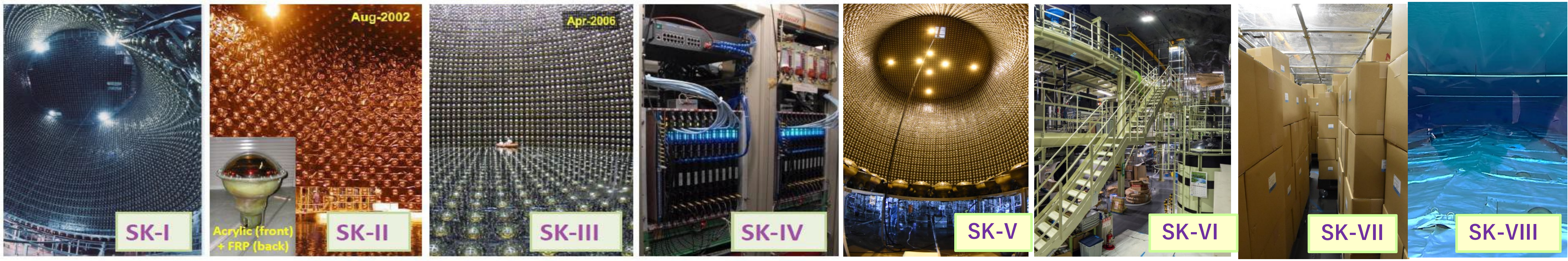
May 24, 2025

Super-Kamiokande History

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 6,511 days live time

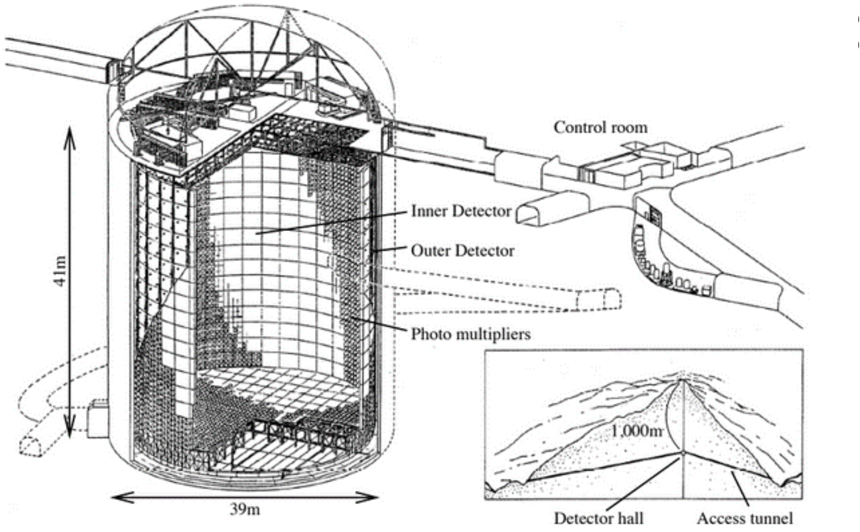
Gd-loaded water
956.2 days + the future…

Super-Kamiokande is now nearly 30 years old

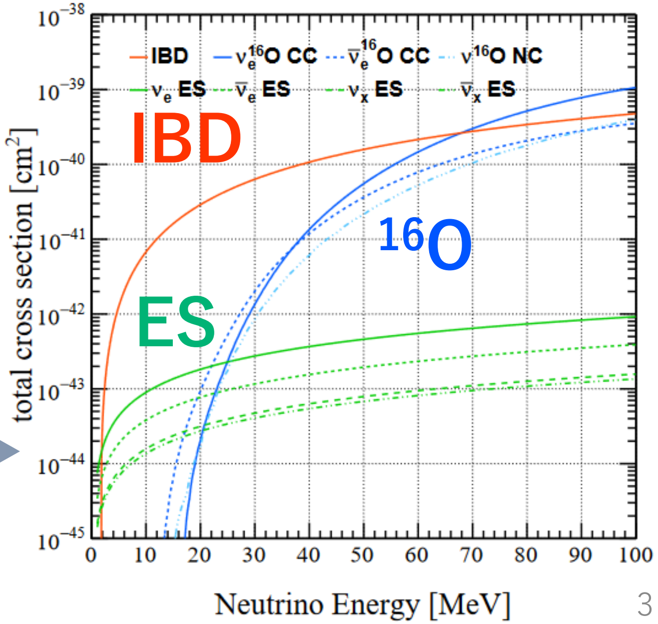
— That's half of Mark Vagins!

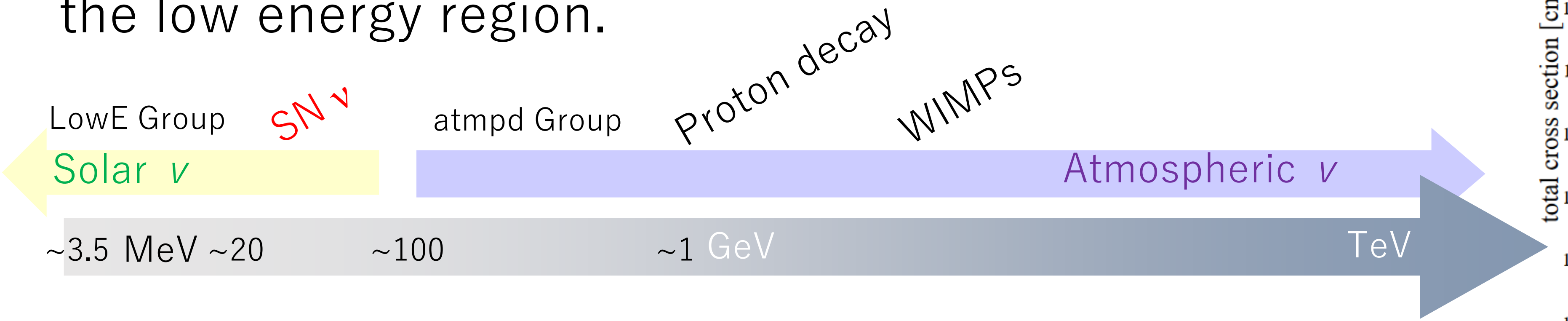
Super-Kamiokande (since July 5, 2022)

- **Ring imaging Gd-doped water Cherenkov detector**
  - **49.5k m^3 of pure water with 16.2 tons of Gd(0.033 w%)**
    - **39 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$**
    - **~75% Neutron capture efficiency**
  - **Target volume 32k m^3 for SN ν offline analysis**
    - **22.5k m^3 for SN n online monitoring**
  - 11129 50cm PMTs for Inner detector
  - 1885 20cm PMTs for outer detector
- 1km (2700 mwe) underground in Kamioka
- Measurable： **Energy**, neutrino **types**, and **direction**
- Most **sensitive to $\bar{\nu}_e$ through inverse beta decay** in the low energy region.



The interaction channels



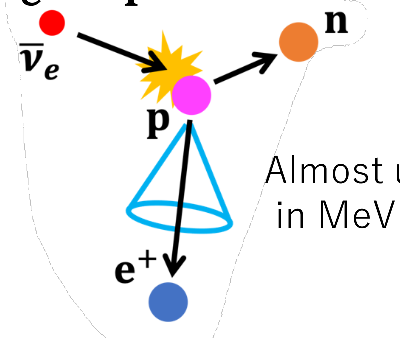


Supernova neutrino in SK

The main channel
Inverse Beta Decay reaction (IBD) ~90%

The direction of the positron does not reflect the direction of the neutrino

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

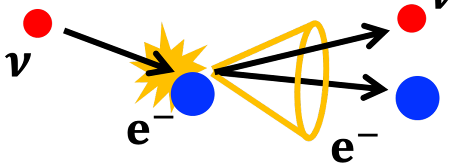


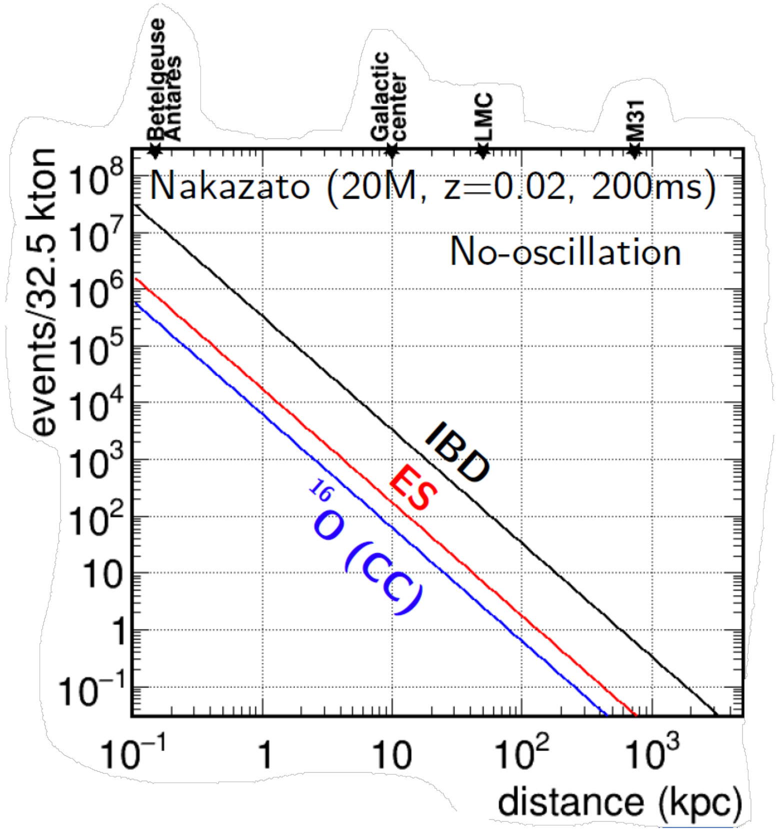
Almost uniform in MeV region

As the neutrino telescope
Elastic Scattering interactions (ES) ~5%

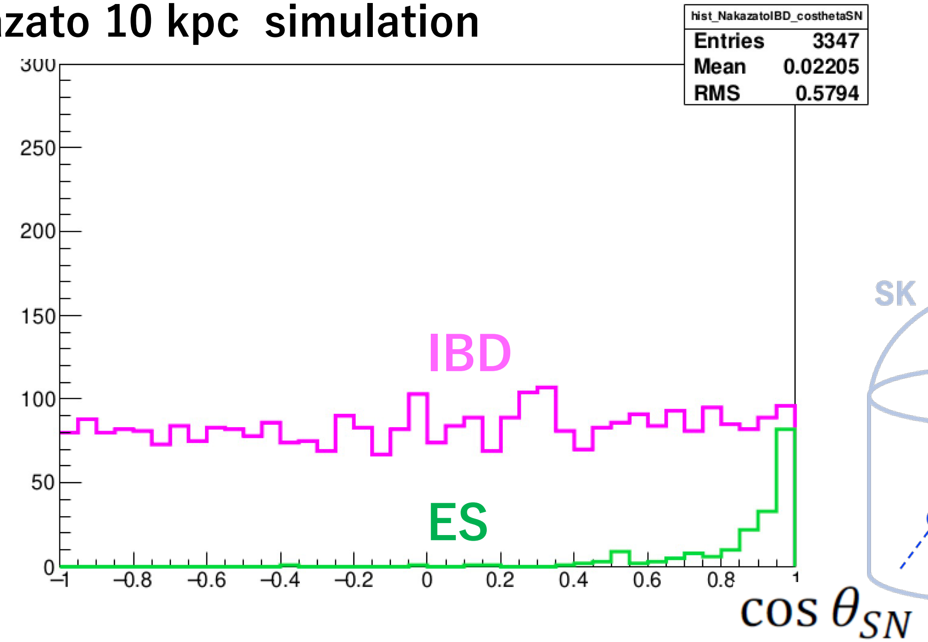
The electron keeps the neutrino direction information.

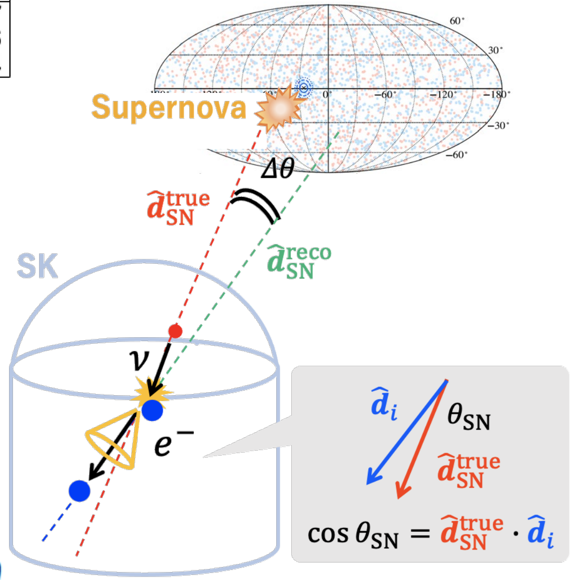
$$\nu + e^- \rightarrow \nu + e^-$$



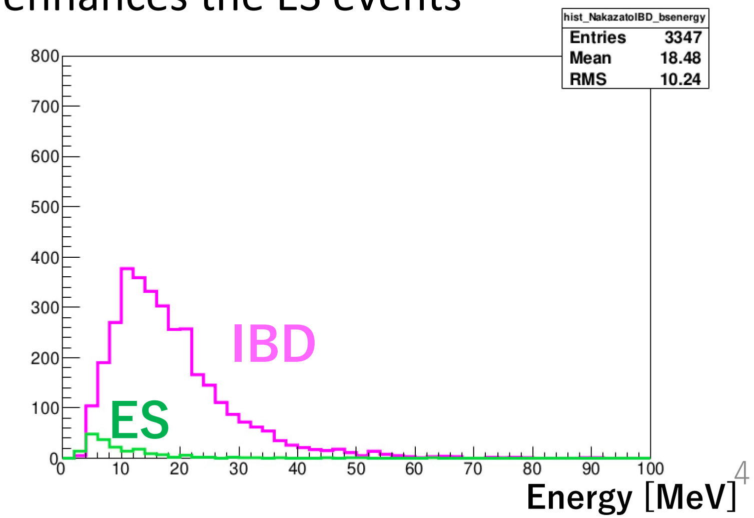


Nakazato 10 kpc simulation





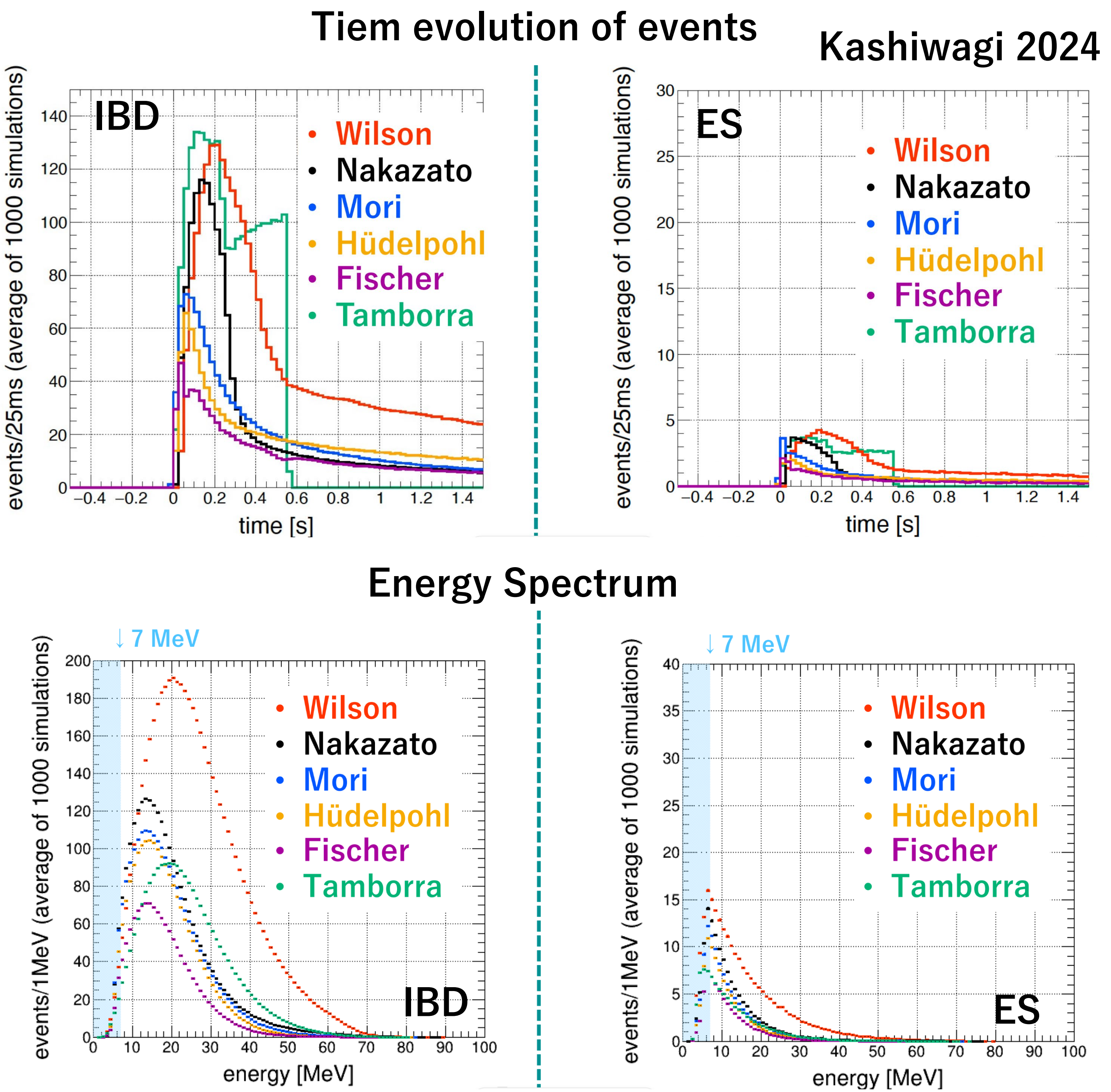
Lowering threshold enhances the ES events



Once a supernova explosion occurs in the Milky Way

- Model discrimination and parameter estimation should be possible using SK’s data.

Just waiting…
with preparation for
Multi-Messenger Astronomy



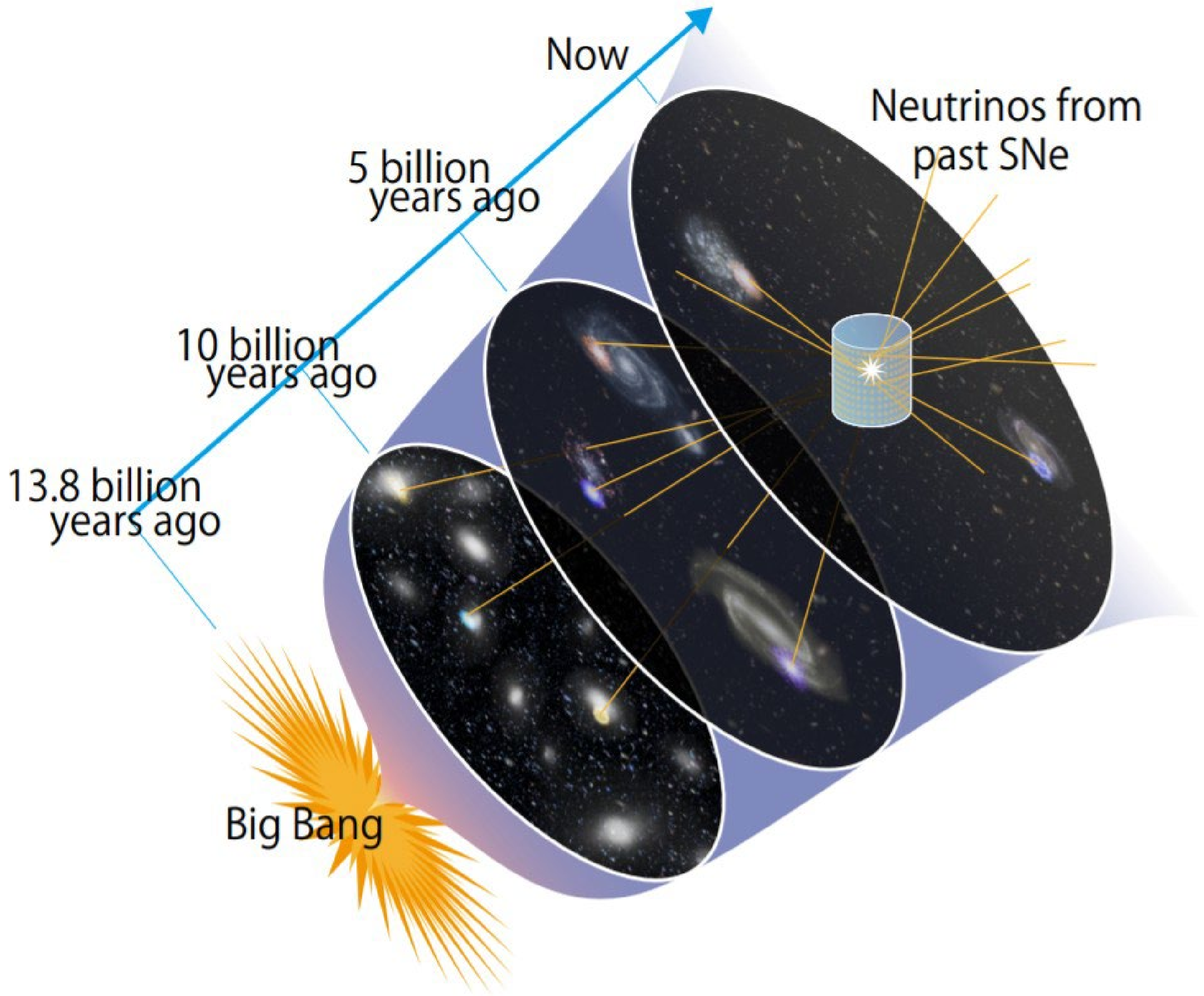
Diffuse Supernova Neutrino Background

Supernova Relic Neutrino

Neutrinos emitted in past supernova explosions and stored in the current universe

Promising extra-galactic ν

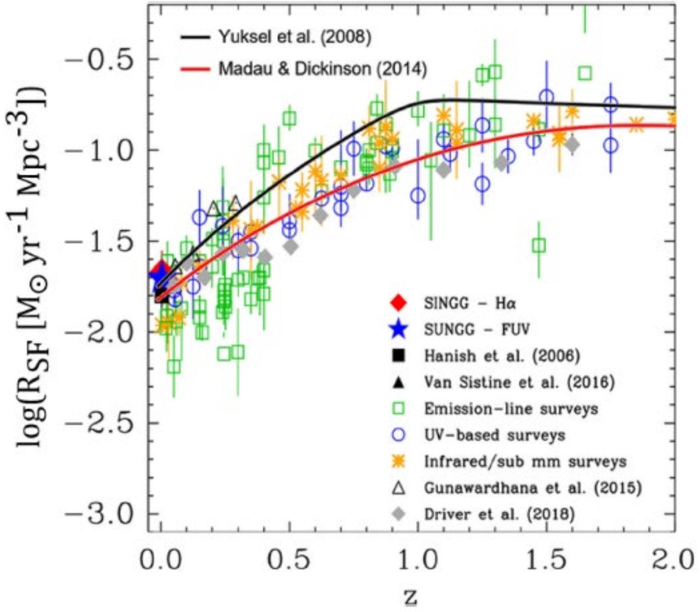
There must have been $O(10^{18})$ explosions in the history of the universe.

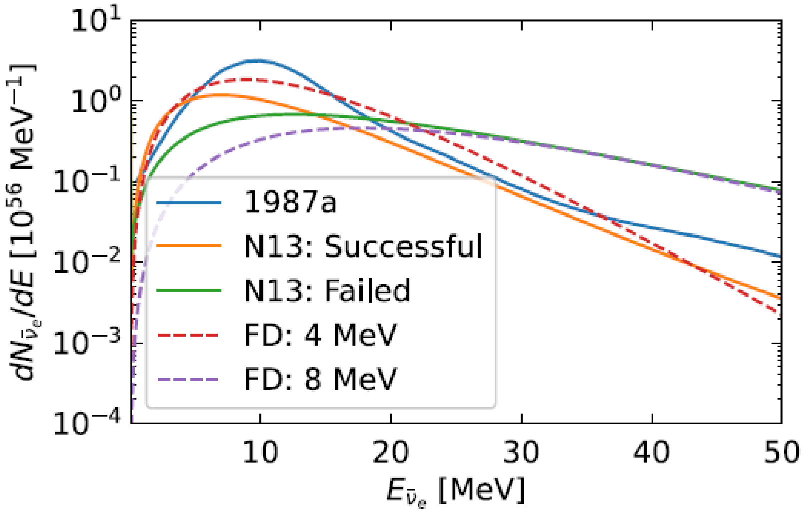


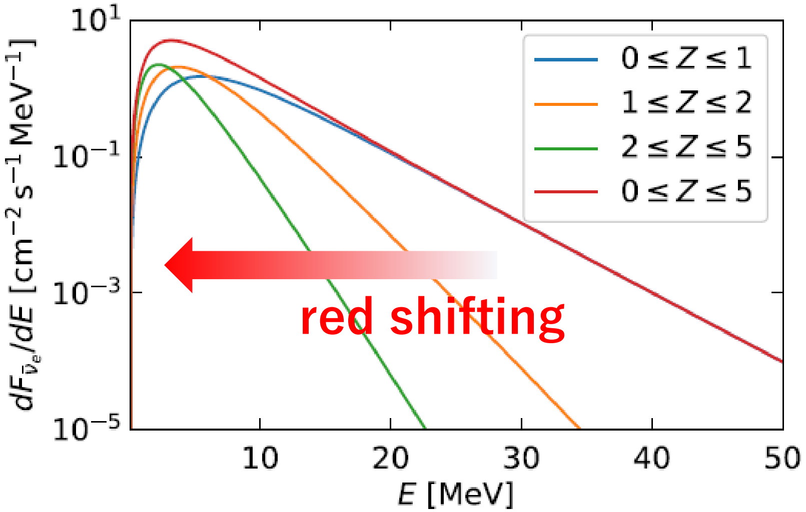
Diffuse Supernova Neutrino Background

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

SN rate at z (averaged)SN spectrum Red shift







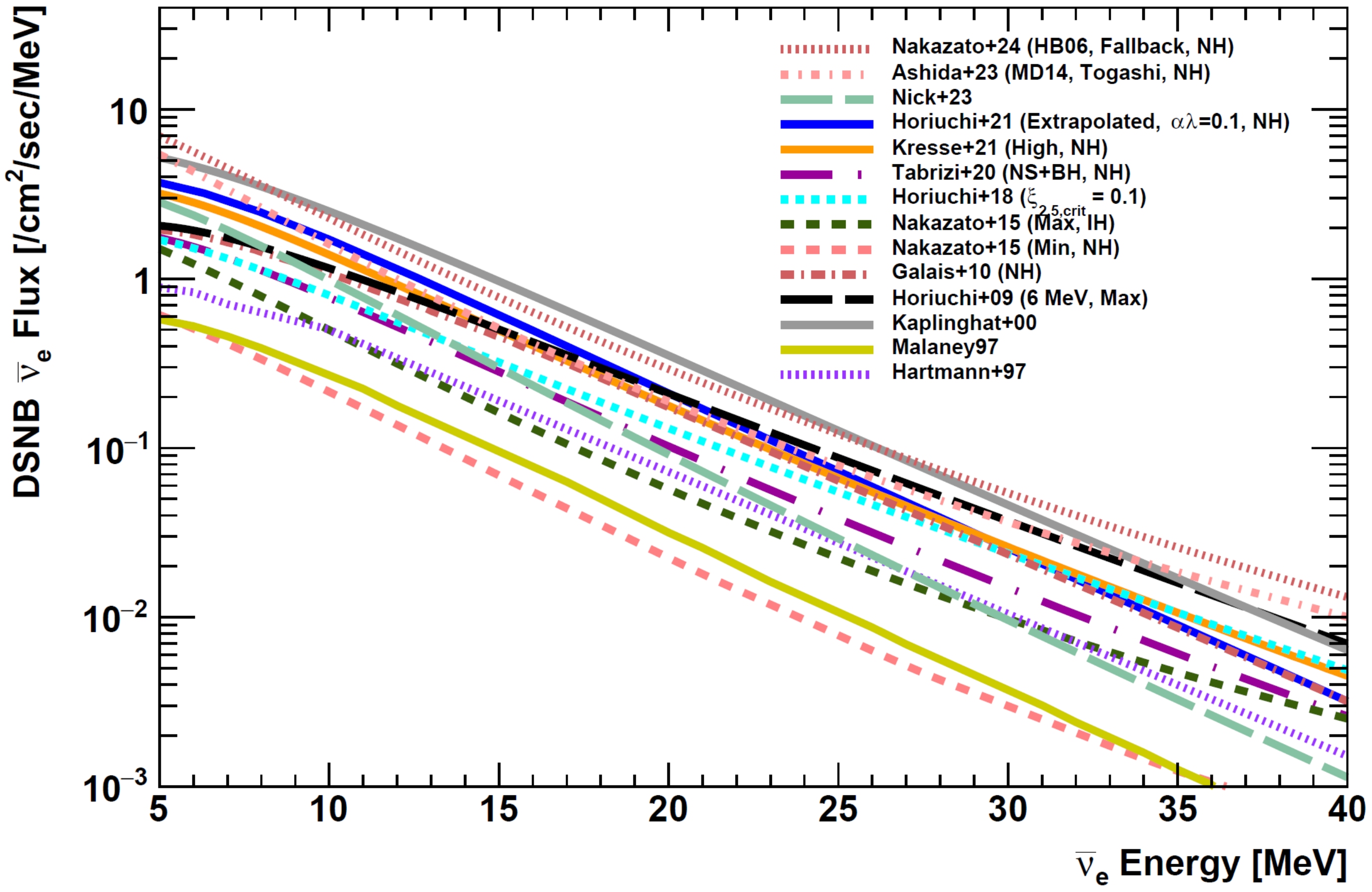
S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

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

Diffuse Supernova Neutrino Background

Many models $\dfrac{dF_\nu}{dE_\nu}$

＋ Neutrino physics
ν MO or/and
exotic process
(ex ν-decay)

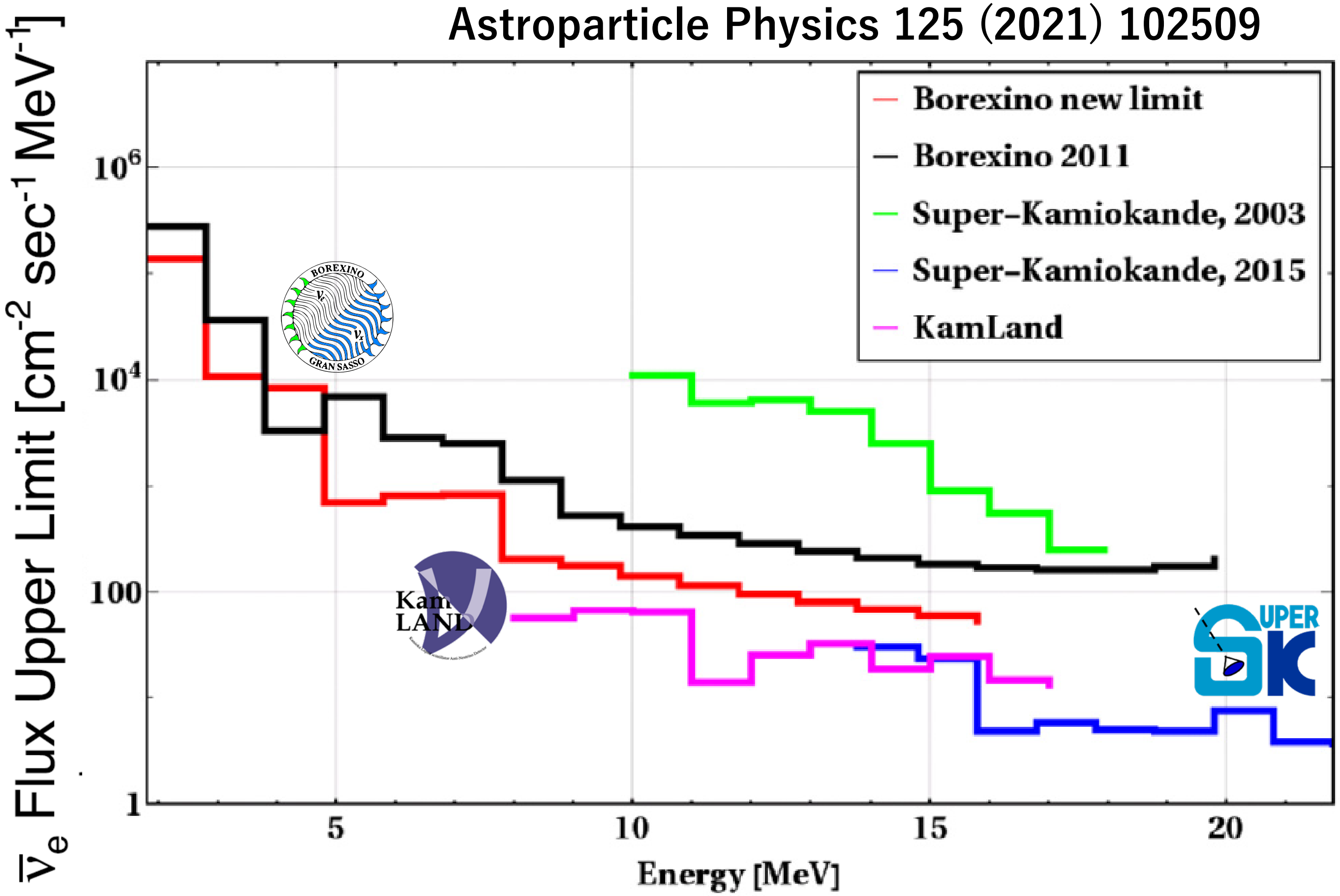


Access to

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

Experimental DSNB search overview@2021

Astroparticle Physics 125 (2021) 102509



Favorable energy range

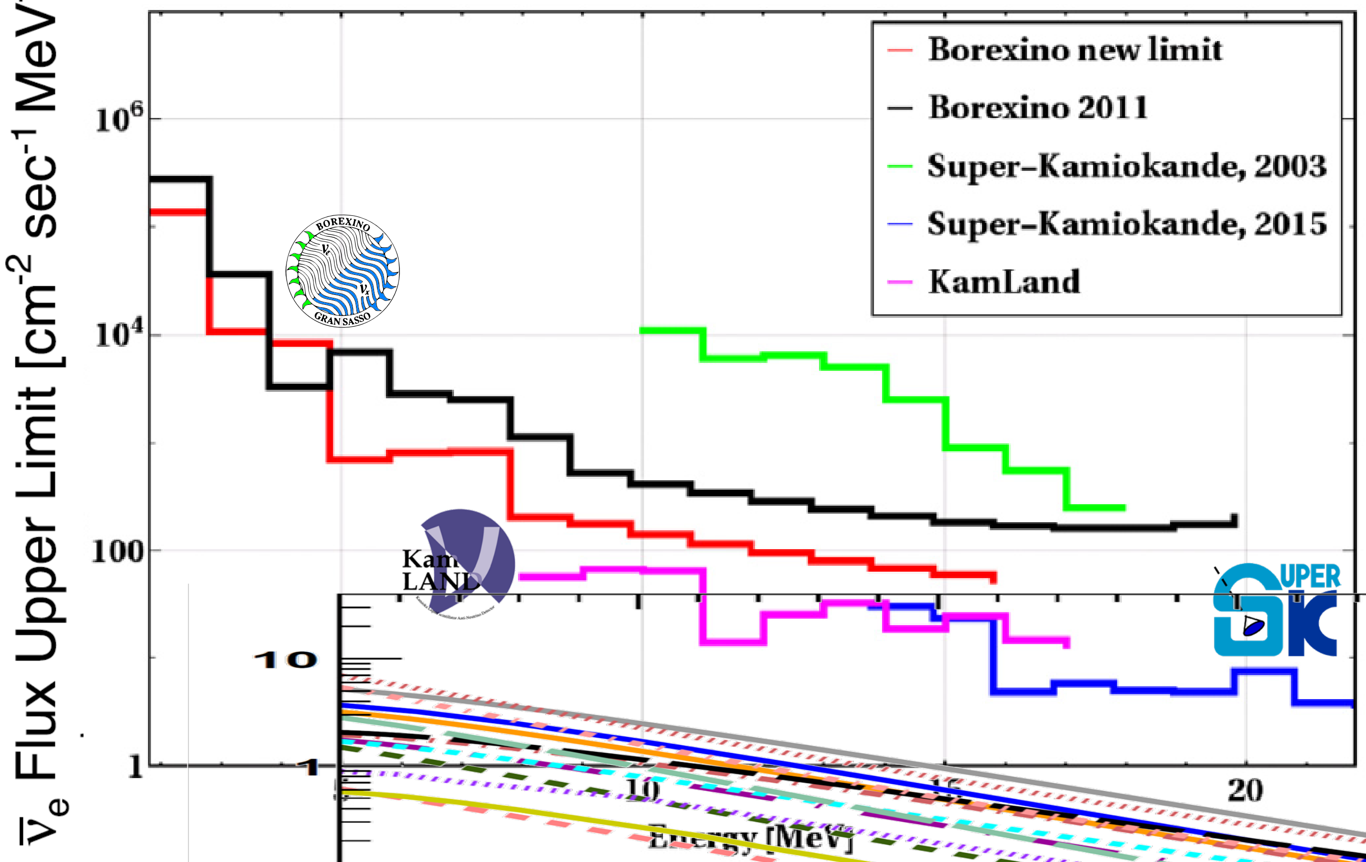
<7MeV Borexino

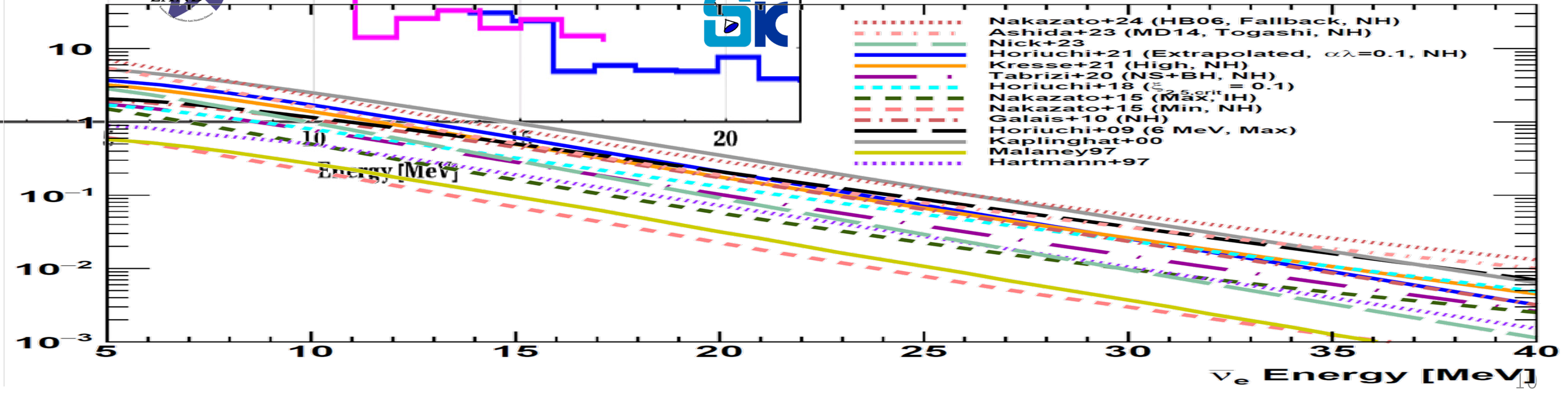
7~13MeV KamLAND

>13MeV SK

Experimental DSNB search overview@2021

Astroparticle Physics 125 (2021) 102509





Favorable energy range

<7MeV **Borexino**

7~13MeV **KamLAND**

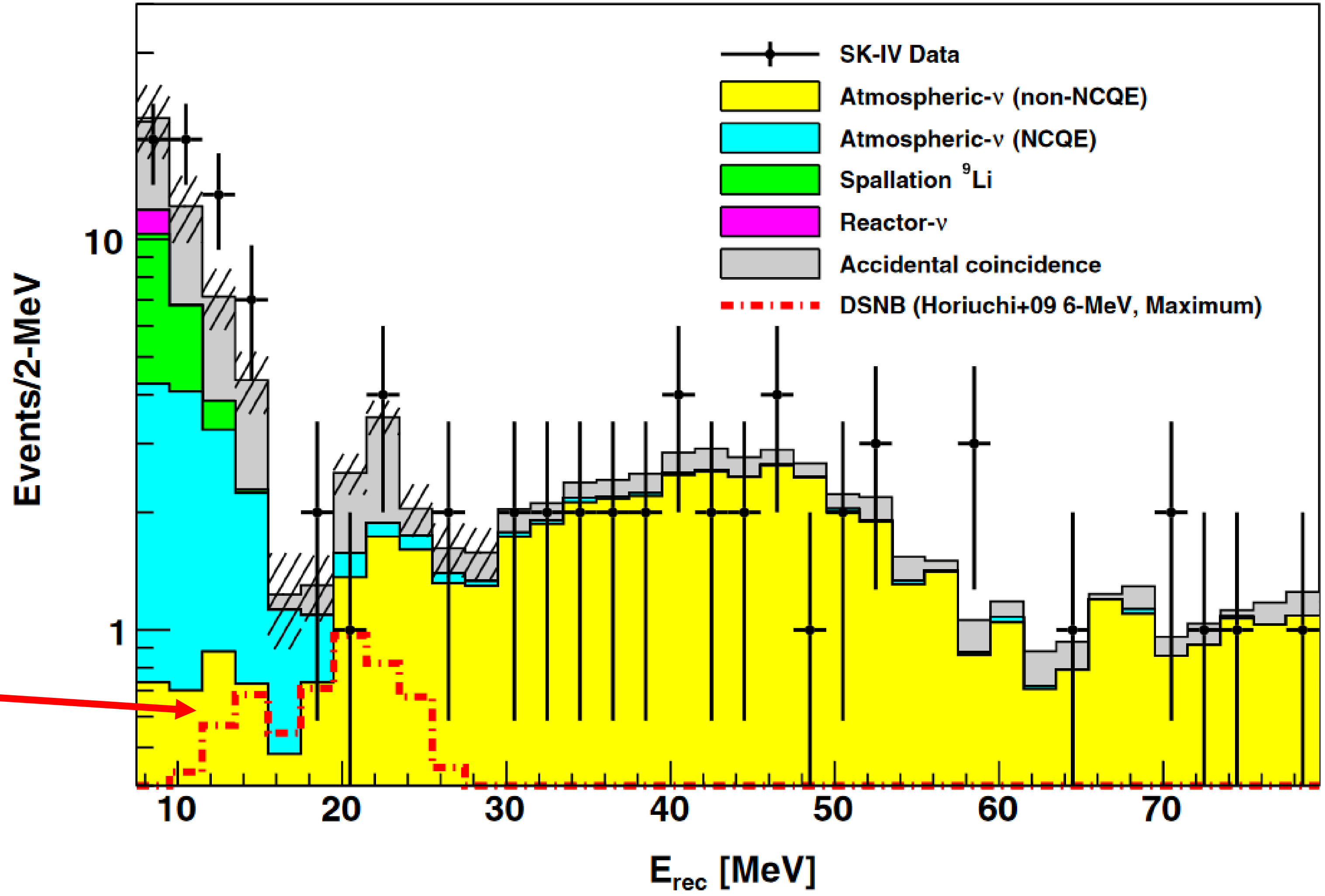
>13MeV **SK**

SK is most likely to get closest to the prediction.

Background of DSNB search

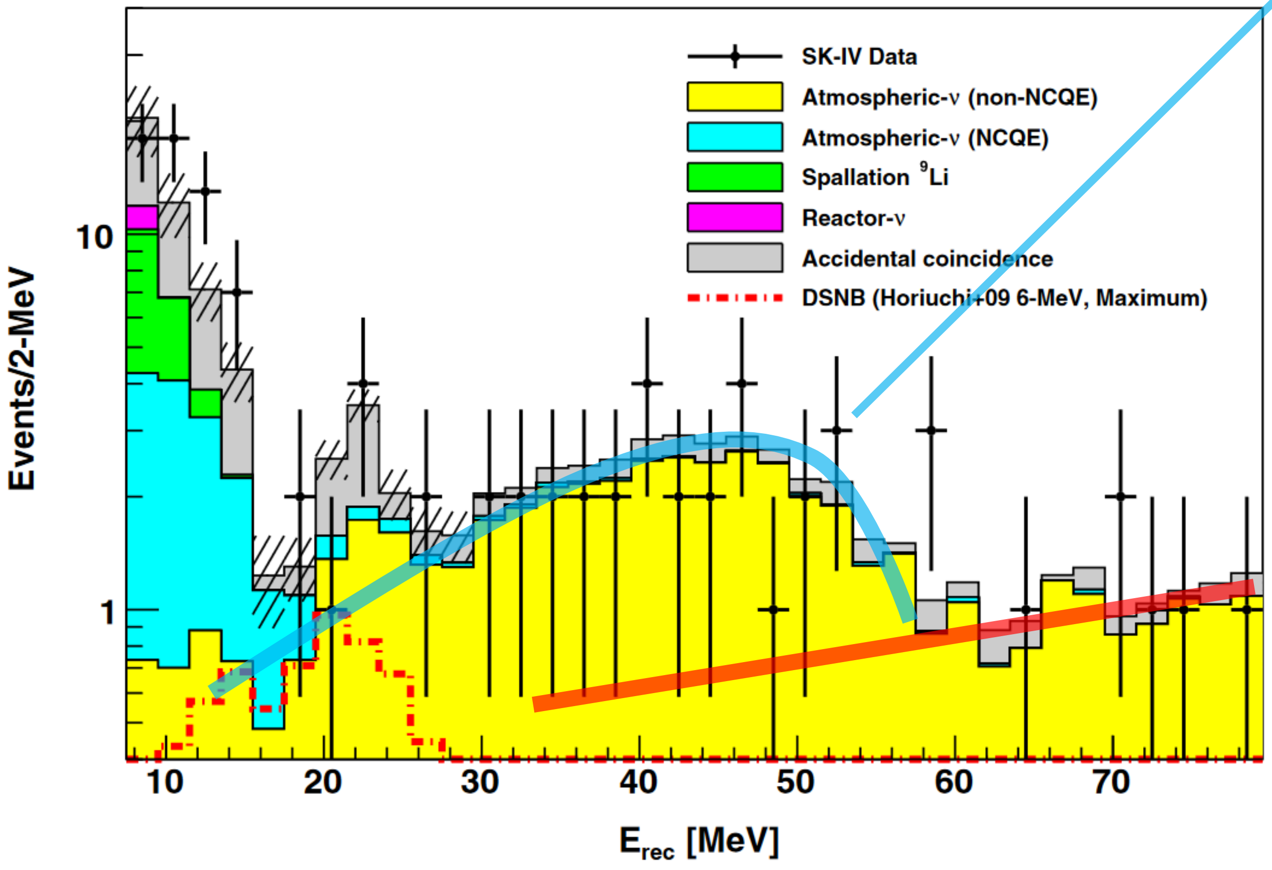
SK-IV (Pure Water Phase)

Phys. Rev. D 104, (2021) 122002

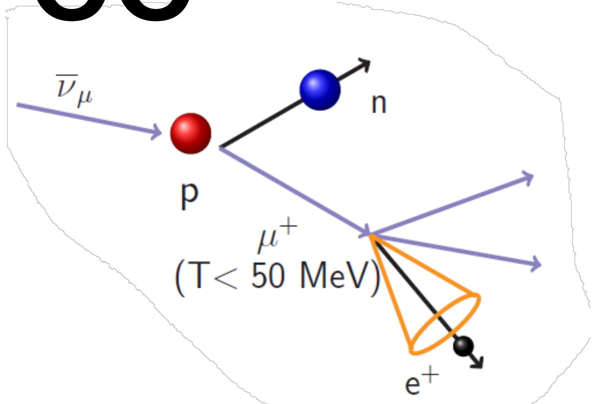


Expected DSNB (Signal)

Background : Atmospheric ν CC

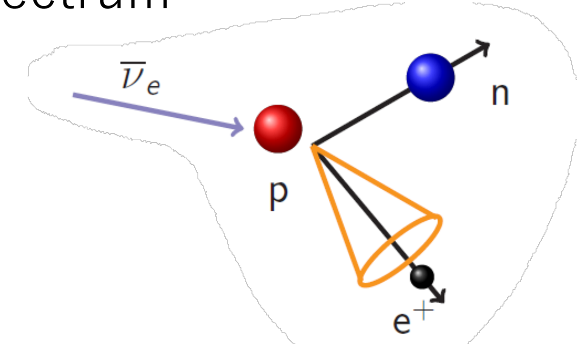


ν_μ CC



- When muons are not visible (below Cherenkov threshold), and only electrons are observed
- The energy distribution is the well-known Michael spectrum

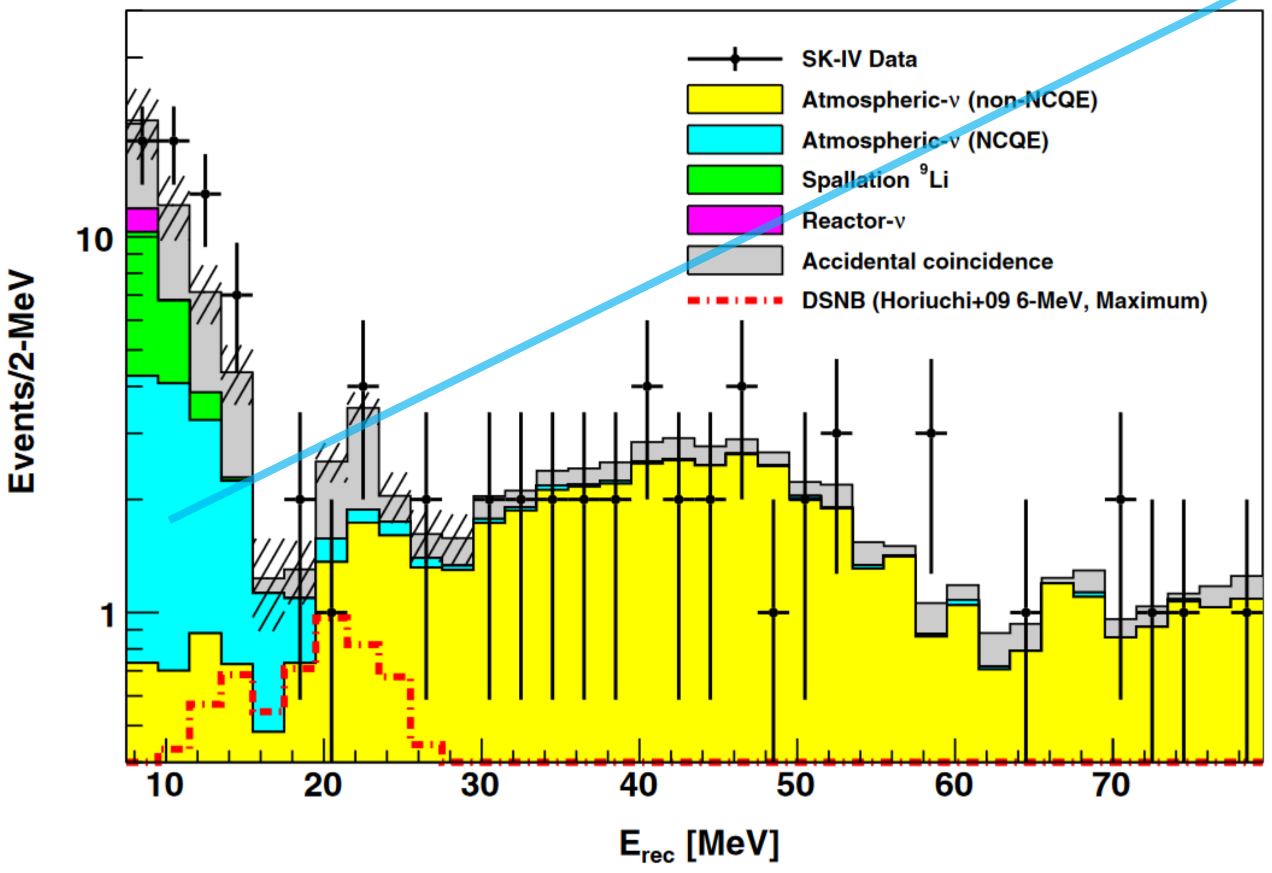
ν_e CC



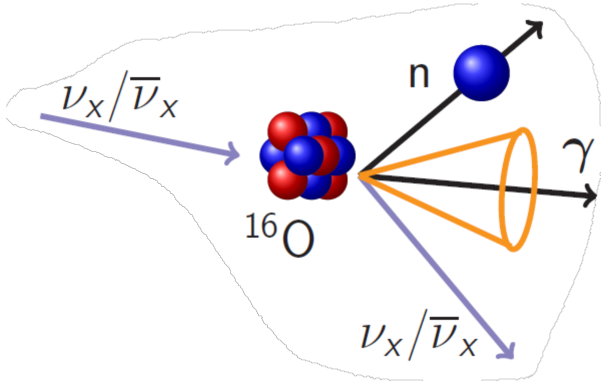
- Major components above 50 MeV
- Small contribution to DSNB region

- These BGs (using >30MeV region) can be estimated **with systematic/statistical uncertainties.**

Background : Atmospheric ν NC



NC(QE)



- Large uncertainty

Atm. ν flux

× NCQE cross-section

(←T2K measurement)

× Number of generated neutrons

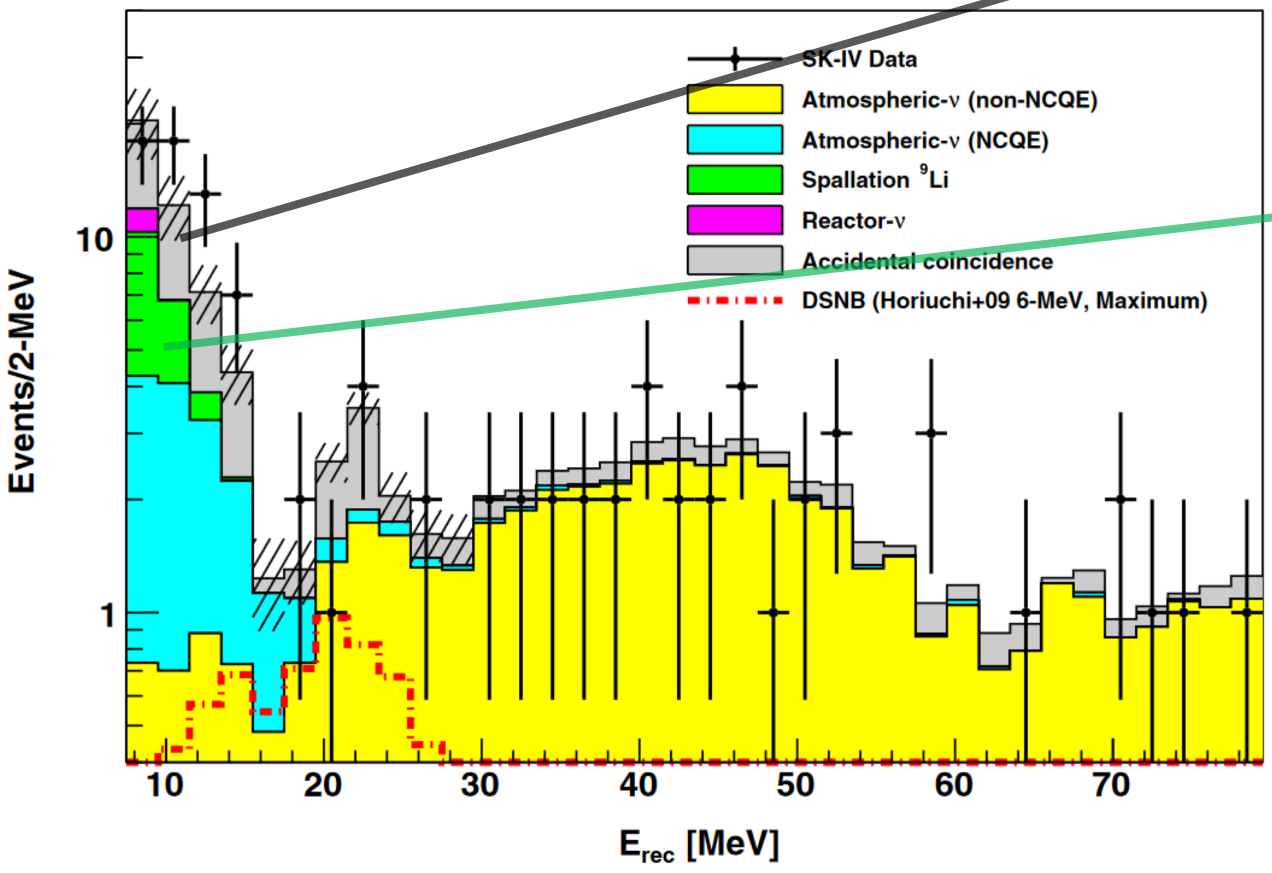
(←T2K measurement)

× Neutron detection efficiency

(←Am/Be calibration)

Understanding and reducing uncertainty is important

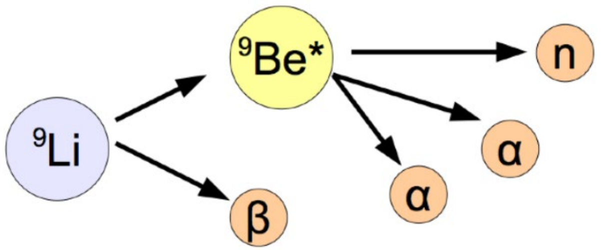
Background : Accidental and Spallation ^{9}Li



Accidental

- Spallation events without neutrons + fake neutron

^{9}Li



- Beta decay + n: same topology as IBD

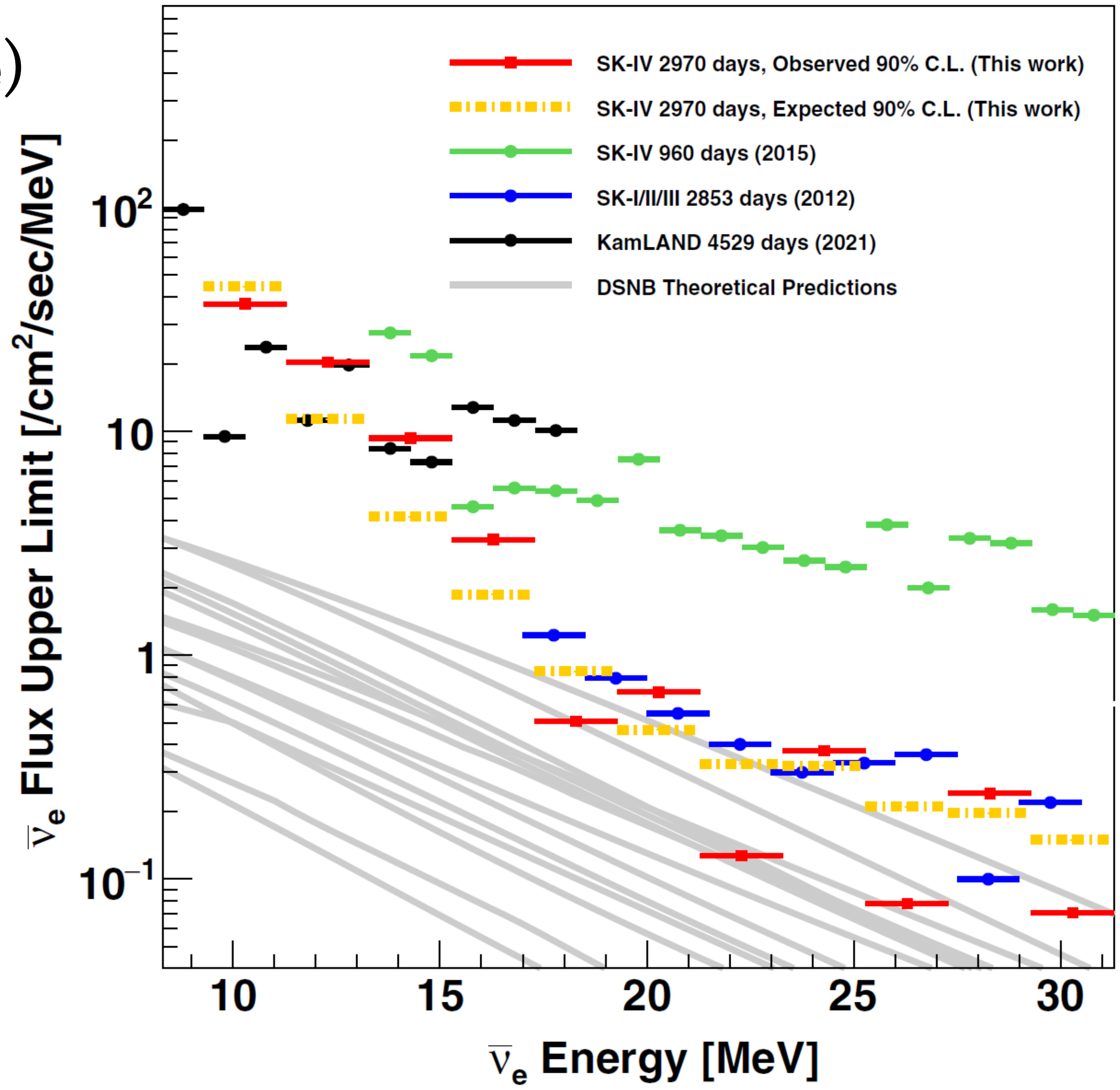
Both can be reduced using the spallation cut and strict neutron selection, but there is a tradeoff with the efficiency of detecting signal events.
→Optimize cut conditions for each energy

Model-independent limit

Phys. Rev. D 104, (2021) 122002

SK-IV 2970 days (Pure Water Phase)

- Strongest limit
  above 15 MeV
- Already reached some model prediction regions

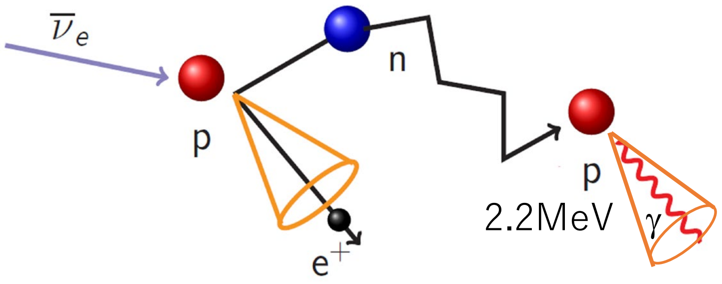


DSNB "signal" search in Water Cherenkov Det.

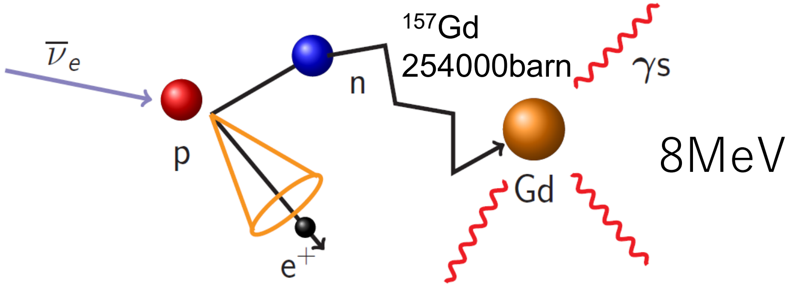
- **Search for inverse-beta decay (IBD)** $\bar{\nu}_e + p \to e^+ + n$
  - Largest cross-section @ DSNB signal range
  - Simple event topology: 1 positron and 1 neutron

→ **Require only one delayed neutrons signal**

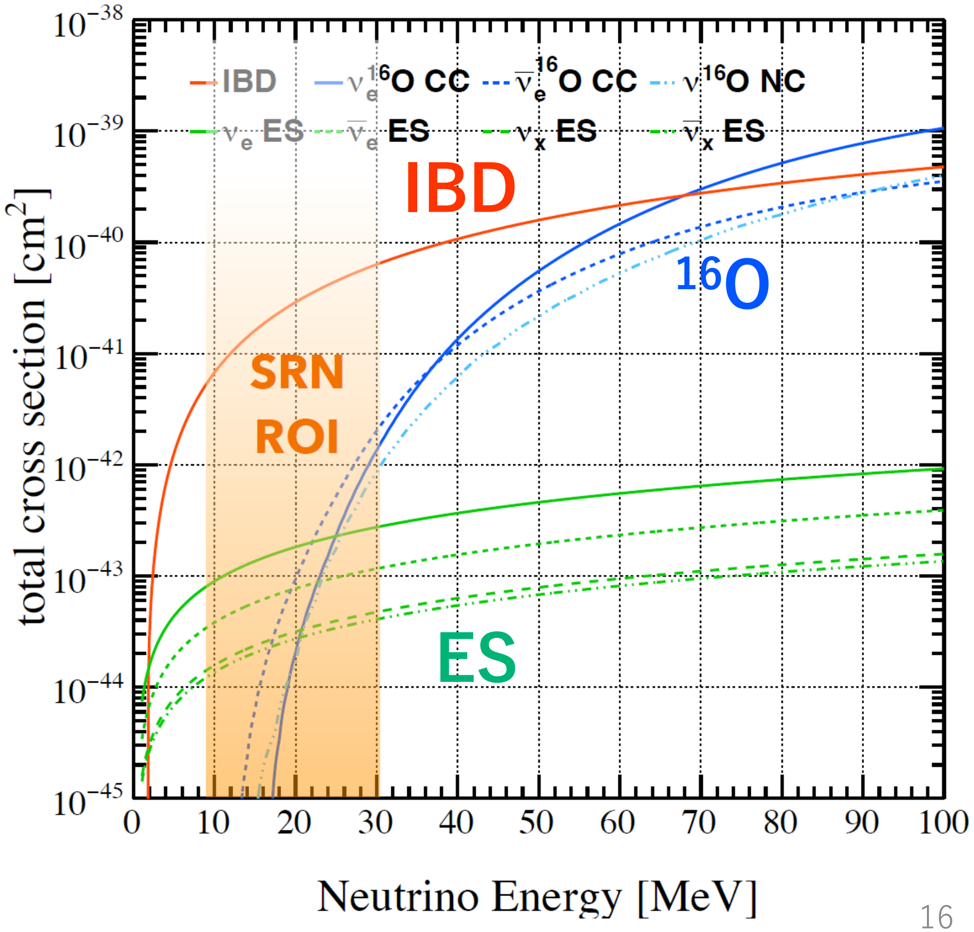
In pure water, the neutron tagging efficiency is low.



Gd-loading improves neutron tagging efficiency.



The interaction channels



Challenges of loading Gd to SK

R&D items in 2016

1st level Environmental Safety

2nd level
Minimize negative impacts to on-going physics programs at SK

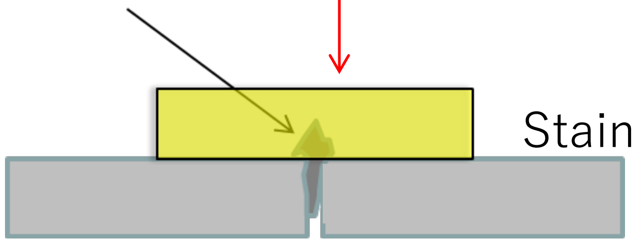
3rd level
Further investigate physics capability with n-tagging

- **Stopping the SK leakage**
  - Estimation of the leak location
  - Development of the leak-fixing method
- **Reduction of RIs from $Gd_2(SO_4)_3$ powder**
  - Test of Ra removal resins
  - Material screening with HP-Ge detectors
  - High sensitivity measurement with ICP-MS
- Test with the EGADS demonstrator
  - Continuous monitoring of the water quality
  - Continuous monitoring of Gd concentration
  - Demonstration of Gd-captured neutron signal/QBEE upgrade
- **Construction of the new water system**
- Gd gamma measurements and improved simulation of Gd capture

Development of Water-sealing material

Cover the welding lines with a highly flexible waterproof sealing material.

Weld joints



Stainless plates

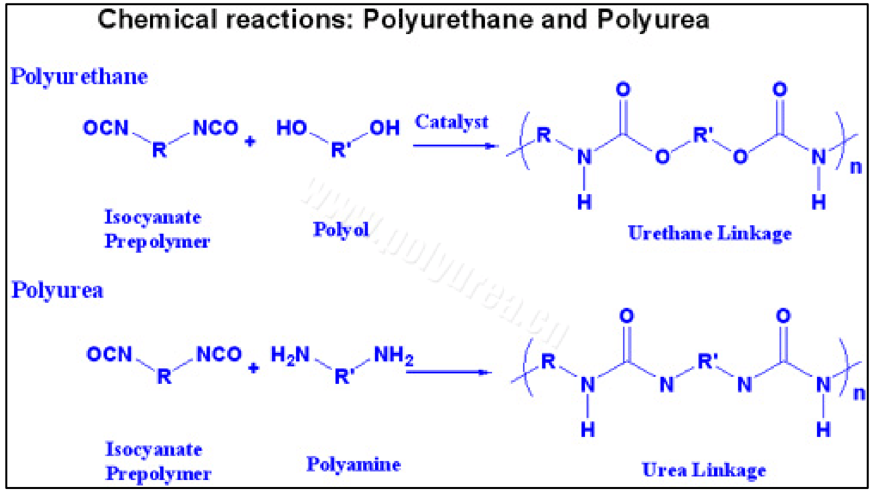
Polyurethane-based materials had a track record of water leakage, not only at SK but also at SNO.

This was due to the hydrolysis of the ester/ether bonds they contain.

To address this issue, we developed a polyurea-based material.

Our special requirement

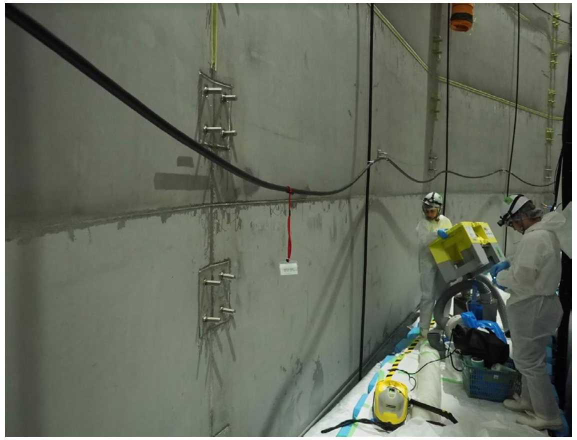
- Materials with minimal elution into the Gd water and that do not degrade water transparency
- Materials with low radon emanation that do not increase the low-energy background



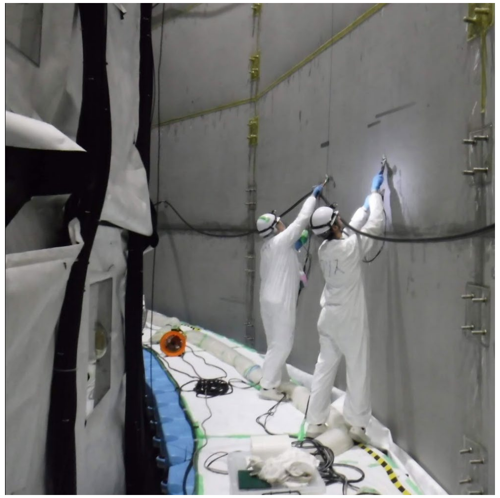
Cleaning before the Painting

- A major cleaning of the 40-meter tank carried out by collaborators and volunteers from around the world

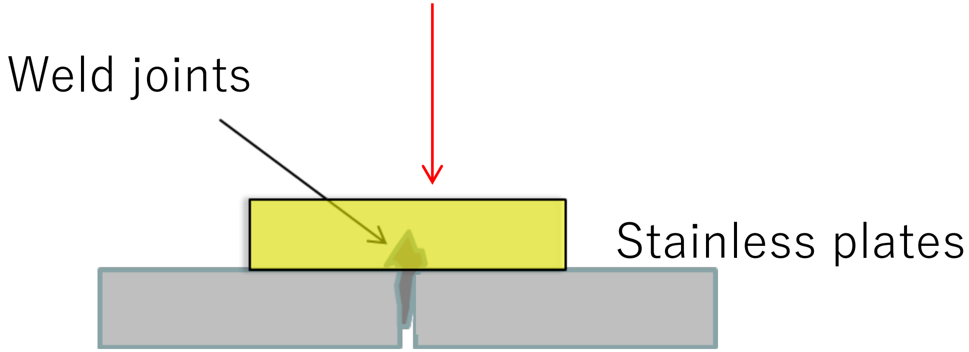






Water-sealing work on the SK tank



Primer painting

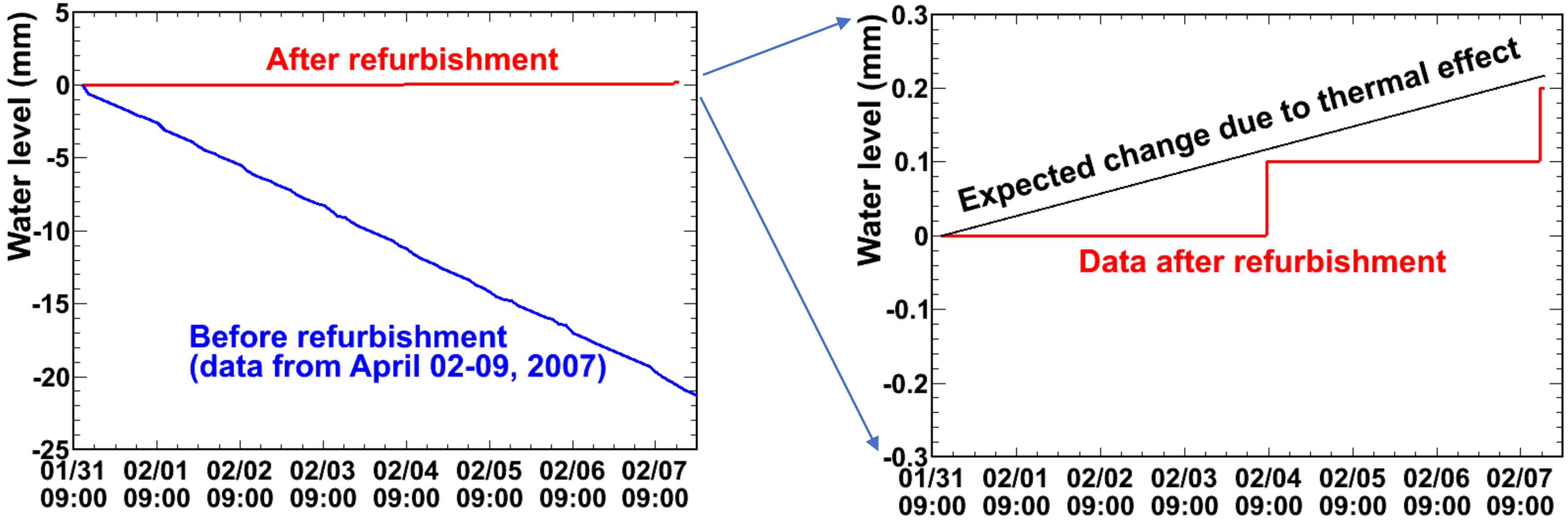
Mixing two materials
(main and curing agent)

Mine-guard painting

Checking and correction

Result of SK tank refurbishment

After completely filling the tank with water, we conducted the water leakage measurement from 11:30 AM on January 31st to 3:52 PM on February 7th, 2019 — a total duration of 7 days, 4 hours, and 22 minutes.



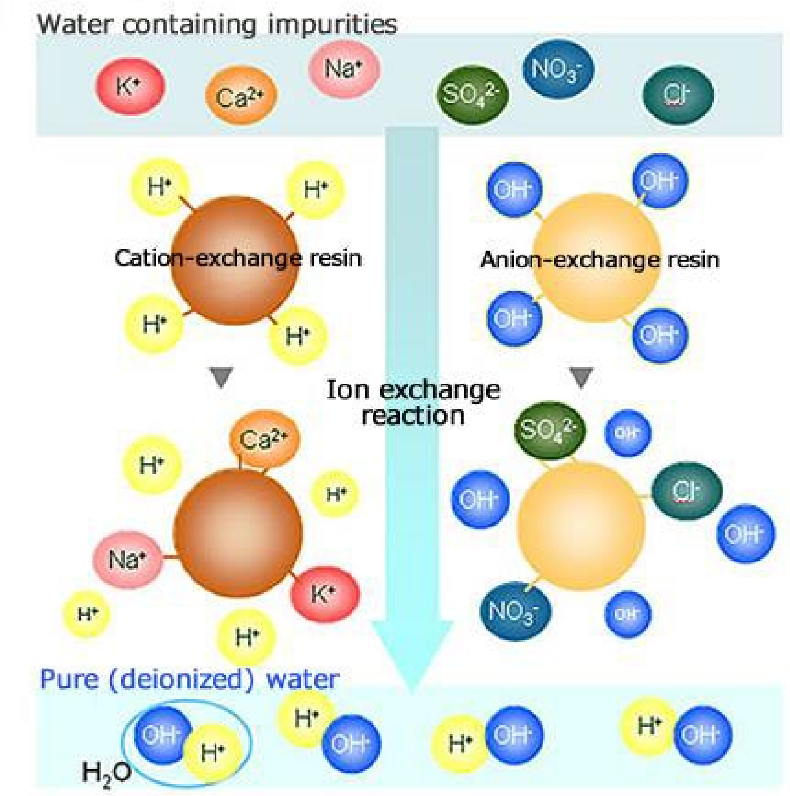
<u>Conclusion</u>

- No water leakage has been observed from the SK tank within the sensitivity of our measurement, which is better than 0.017 tons per day.
- This corresponds to less than 1/200th of the leak rate recorded before the 2018–2019 tank refurbishment.

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

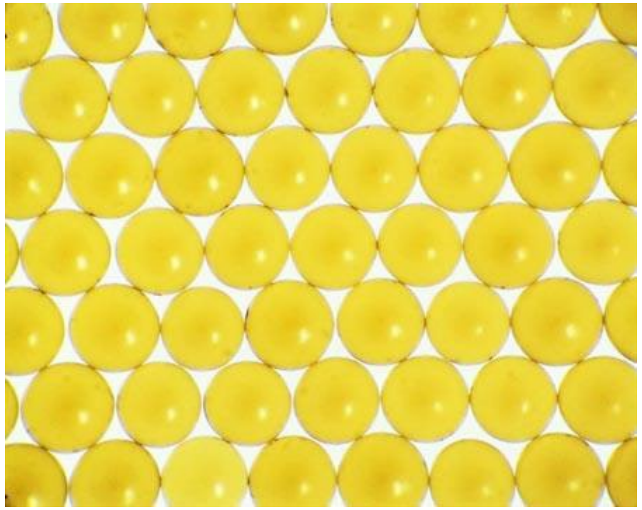


Development of special ion exchange resins

Anion exchange resin $OH^- \rightarrow SO_4^{2-}$

Cation exchange resin $H^+ \rightarrow Gd^{3+}$

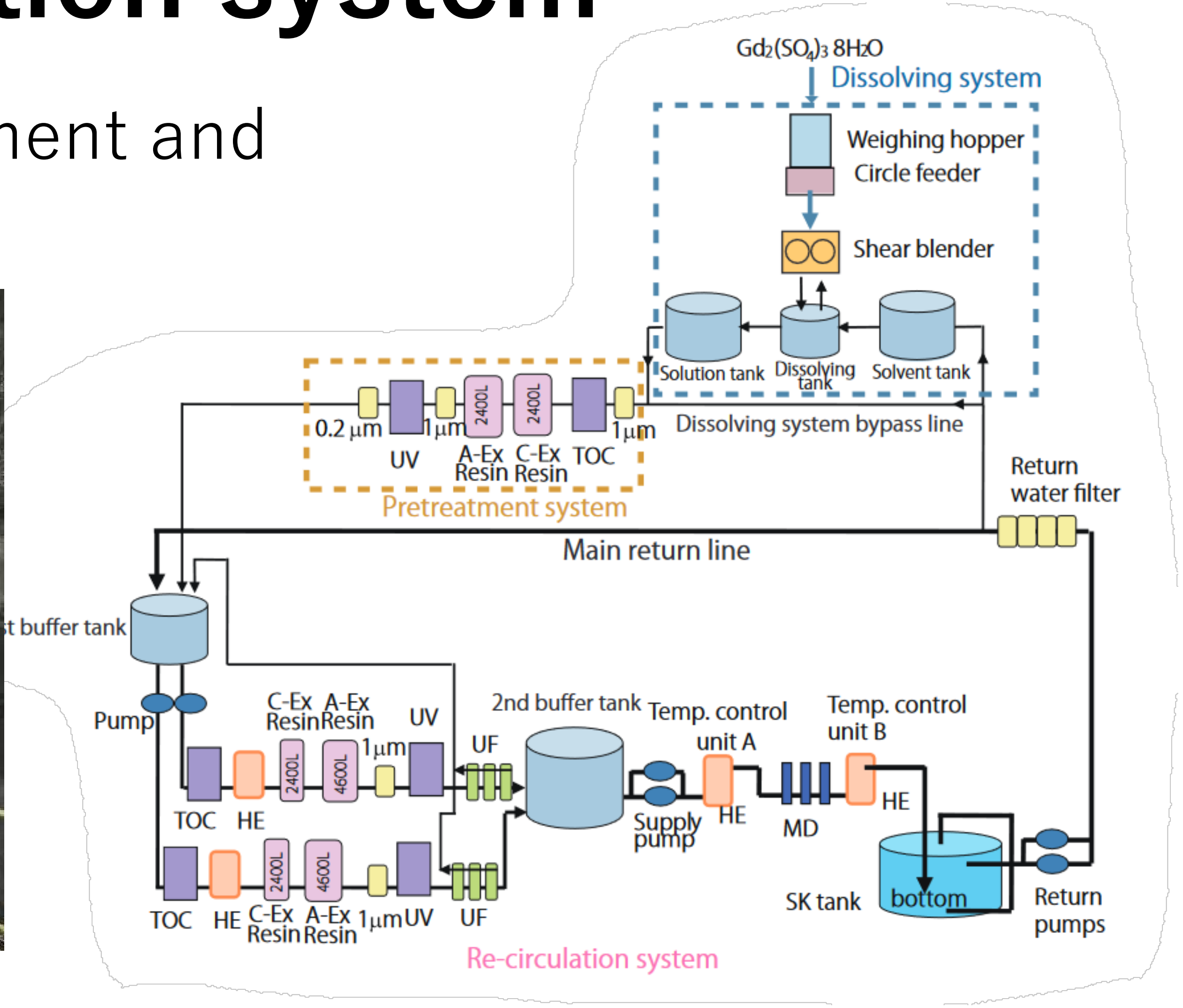
RI impurities (Ra^{2+}, $UO_2(SO_4)_3^{4-}$ etc.) are also removed.



NIMA 1027 (2022) 166248

Pretreat + Recirculation system

- The resins are used for pretreatment and recirculation processes



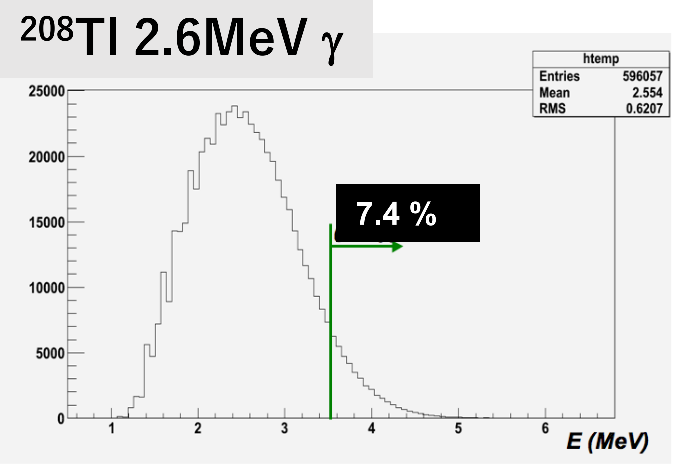
- The recirculation flow rate had been doubled to 120m^3/h

Required purity of $Gd_2(SO_4)_3{\cdot}8H_2O$

- Radioactive impurities (^{238}U, ^{232}Th, etc.) affect SK's solar neutrino observations above 3.5MeV due to energy resolution.
- 99.999% high purity products contain 50~100 mBq/kg of RIs.

RI levels of Typical 5N $Gd_2(SO_4)_3{\cdot}8H_2O$ → **Simulated energy spectrum in SK**

Chain	**Main sub-chain isotope**	Radioactive concentration (mBq/kg)
^{238}U	**^{238}U**	50
	^{226}Ra	5
^{232}Th	**^{228}Ra**	10
	^{228}Th	100
^{235}U	**^{235}U**	32
	^{227}Ac/ ^{227}Th	300



→ After cuts applied

~3 x 10 ^{5} events/day/ FV

SK-IV Rn BG for solar neutrino analysis ~200events/day/FV

→ **3 orders reduction**

The difficulty that we overcome;
- **Homogeneous production of 40 tons of powder**
- **Evaluation methods**

Required RI levels

^{238}U < 5mBq/kg = 400 ppt

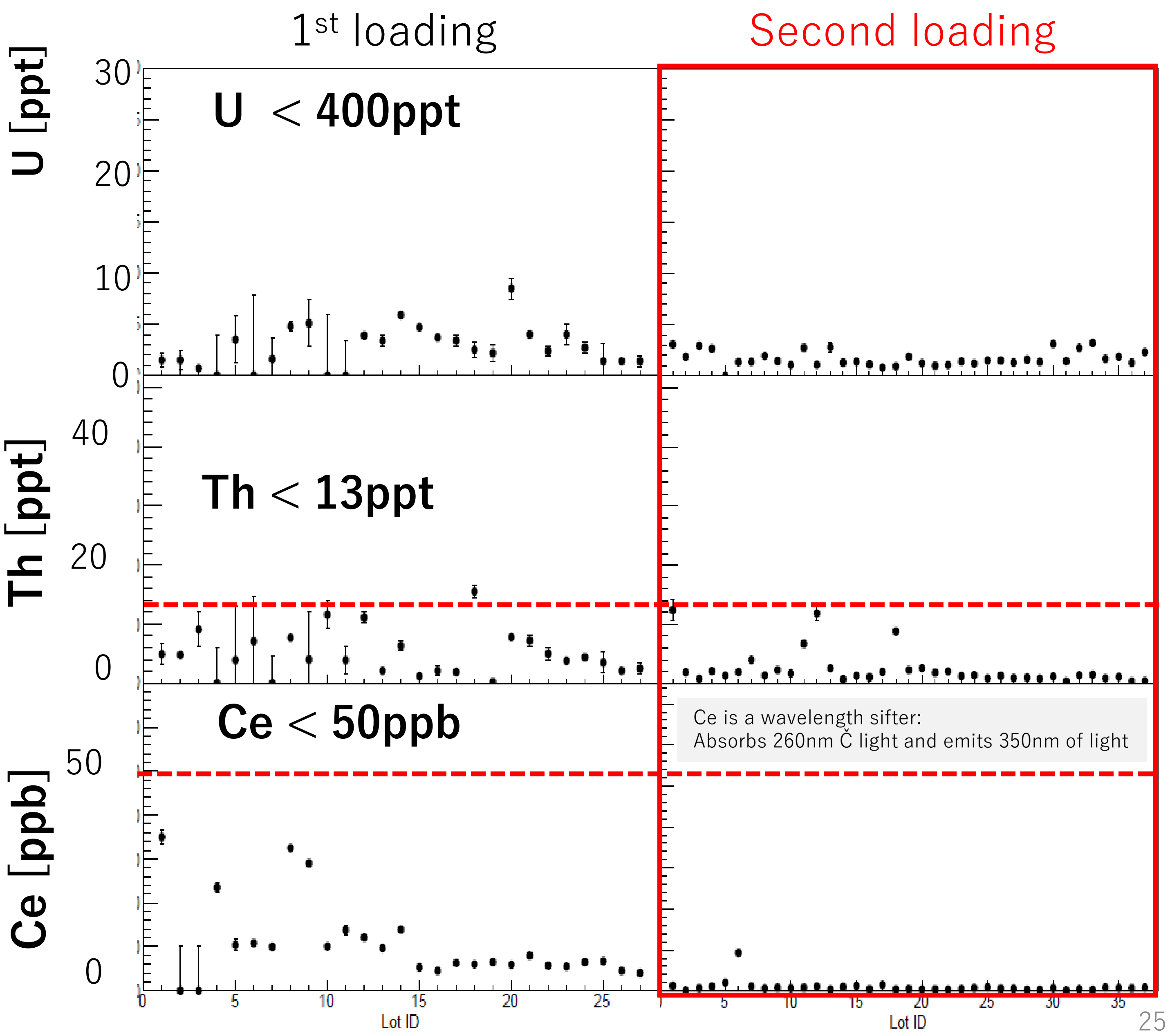
^{232}Th < 0.05mBq/kg = 13ppt

Purer Gd arXiv:2209.07273

- **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

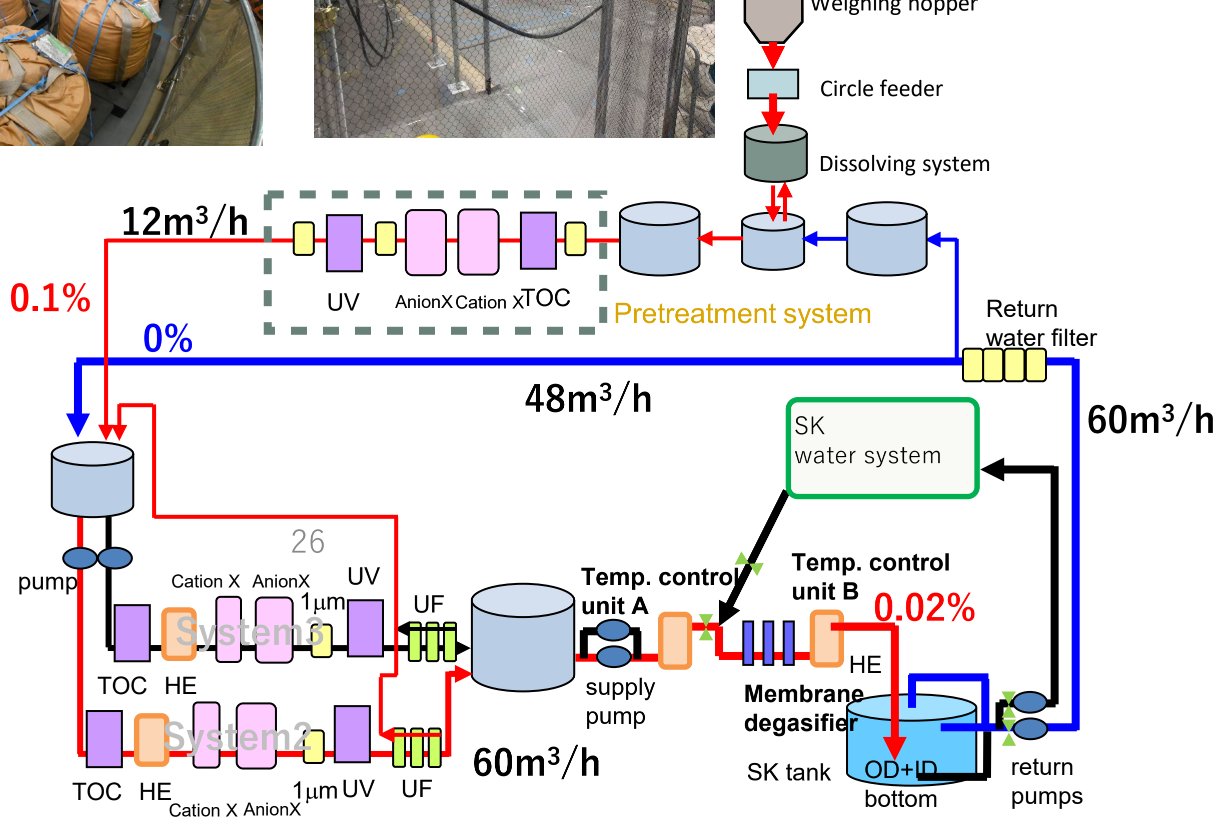


The 1st Gd-loading Jul. 14 – Aug. 18, 2020

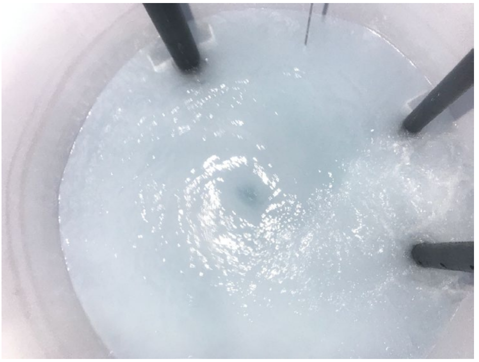
The pure water in the SK tank was taken from the top and returned from the bottom in **0.02% $Gd_2(SO_4)_3$** solution **(=0.01% Gd = 0.026% $Gd_2(SO_4)_3 \cdot 8H_2O$)**
It took 35 days to replace 50,000 tons of water at 60 m^3/h

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



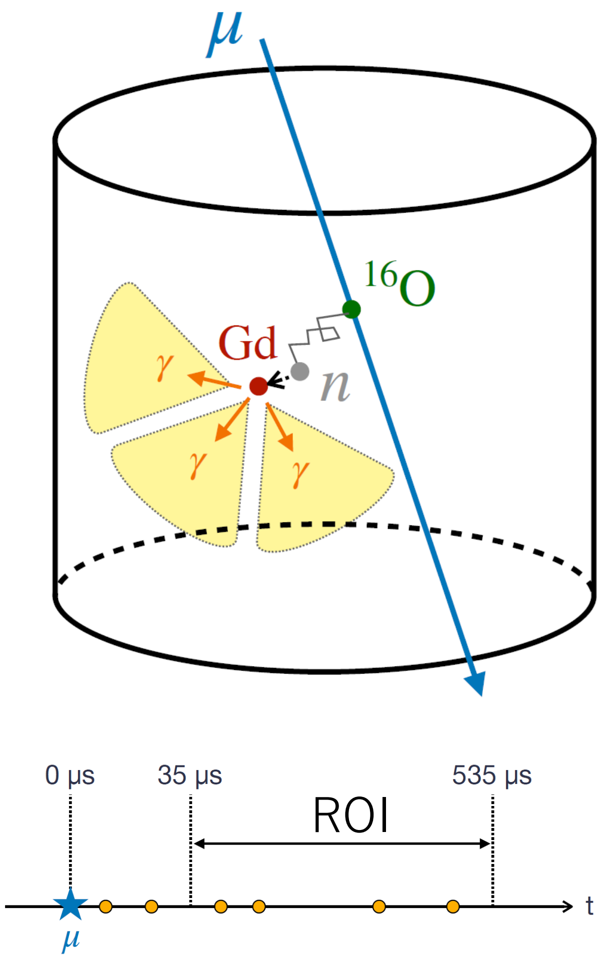
Just after mixing



10minutes later

Spallation neutron for Gd check

- μ-induced spallation neutrons (the BG events!) were used for Gd concentration monitoring



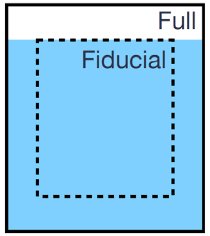
List of spallation products

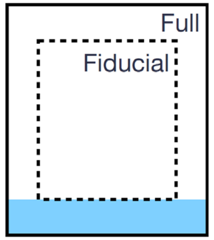
S.Li and J.Beacom, Phys. Rev. C 89, 045801 (2014)

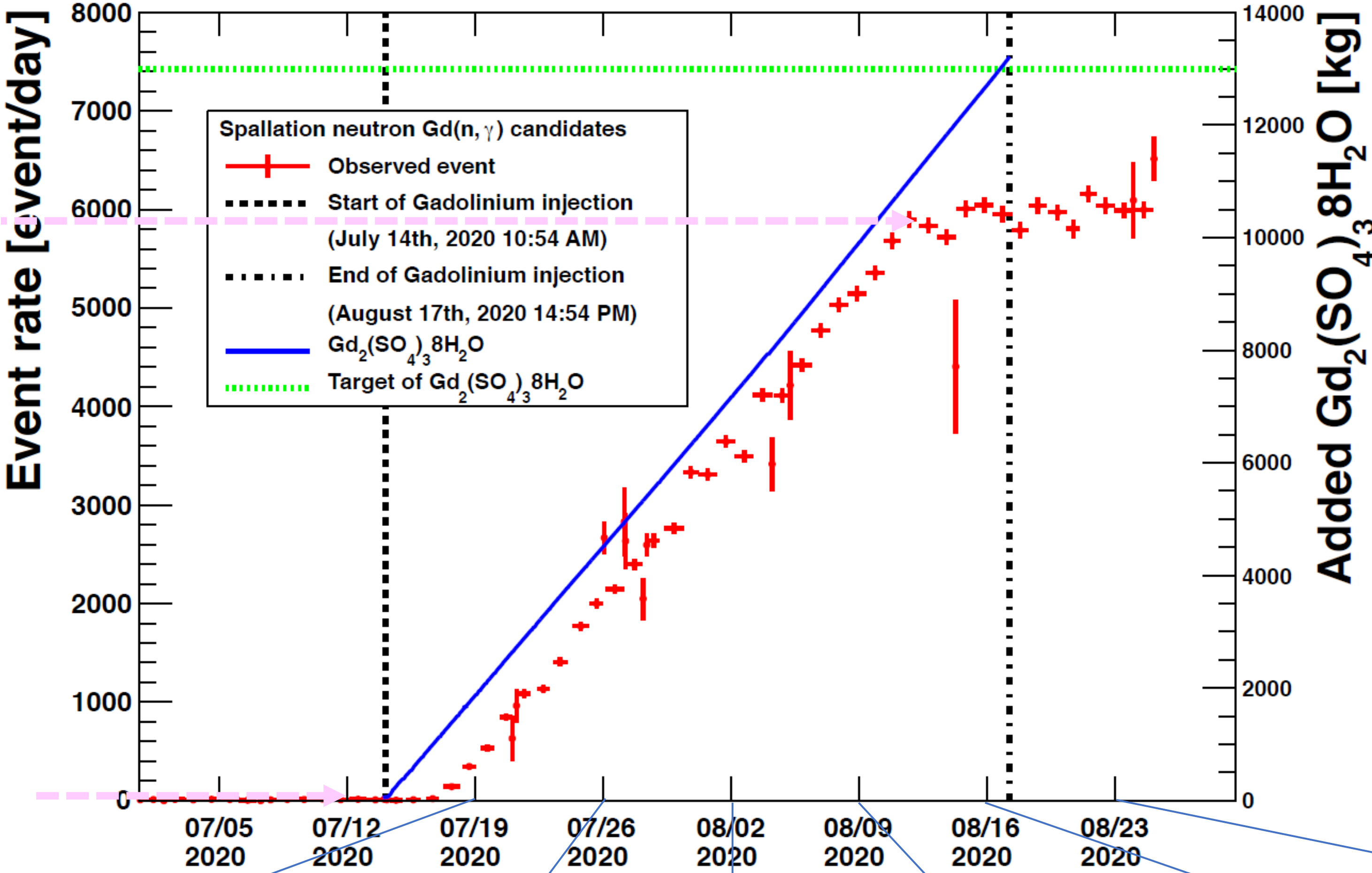
Isotope	Half-life (s)	Decay mode	Yield (total) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Yield (E > 3.5 MeV) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	^{18}O(n,p)
^{17}N	4.173	$\beta^- n$	0.59	0.02	^{18}O(n,n+p)
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	18	(n,p)
^{16}C	0.747	$\beta^- n$	0.02	0.003	(π^-,n+p)
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	0.28	(n,2p)
^{14}B	0.0138	$\beta^-\gamma$	0.02	0.02	(n,3p)
^{13}O	0.0086	β^+	0.26	0.24	(μ^-,p+2n+μ^-+π^-)
^{13}B	0.0174	β^-	1.9	1.6	(π^-,2p+n)
^{12}N	0.0110	β^+	1.3	1.1	(π^+,2p+2n)
^{12}B	0.0202	β^-	12	9.8	(n,α+p)
^{12}Be	0.0236	β^-	0.10	0.08	(π^-,α+p+n)
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	0.54	(n,α+2p)
^{11}Li	0.0085	$\beta^- n$	0.01	0.01	(π^+,5p+π^++π^0)
^{9}C	0.127	β^+	0.89	0.69	(n,α+4n)
^{9}Li	0.178	$\beta^- n$ (51%), β^- (49%)	1.9	1.5	(π^-,α+2p+n)
^{8}B	0.77	β^+	5.8	5.0	(π^+,α+2p+2n)
^{8}Li	0.838	β^-	13	11	(π^-,α+^{2}H+p+n)
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%)	0.23	0.16	(π^-,^{3}H+4p+n)
^{15}O			351		(γ,n)
^{15}N			773		(γ,p)
^{14}O			13		(n,3n)
^{14}N			295		(γ,n+p)
^{14}C			64		(n,n+2p)
^{13}N			19		(γ,^{3}H)
^{13}C			225		(n,^{2}H+p+n)
^{12}C			792		(γ,α)
^{11}C			105		(n,α+2n)
^{11}B			174		(n,α+p+n)
^{10}C			7.6		(n,α+3n)
^{10}B			77		(n,α+p+2n)
^{10}Be			24		(n,α+2p+n)
^{9}Be			38		(n,2α)
sum			3015	50	

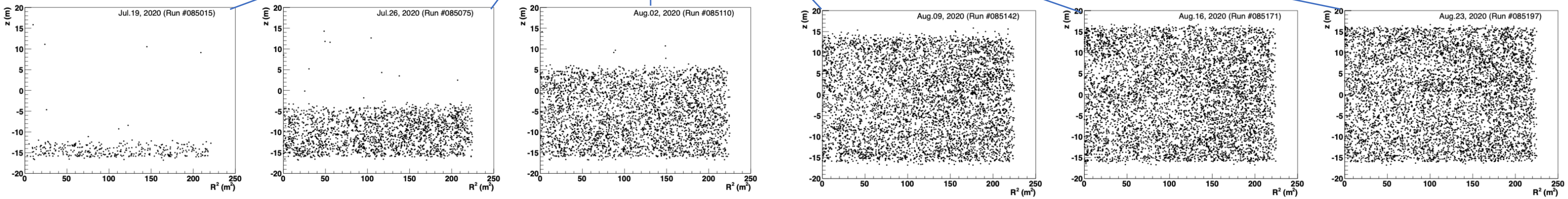
Neutron event rates vs. Gd-loading

Phys. Rev. D 107, 092009 (2023)



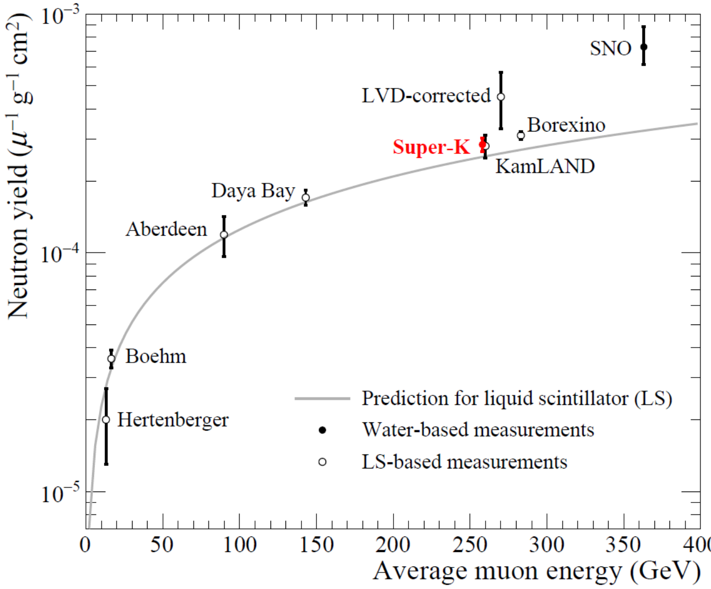






The result of neutron yield measurement:

Y_n = (2.81 ± 0.06 (stat.) ± 0.18 (syst.)) × 10^{-4} $\mu^{-1}g^{-1}cm^2$



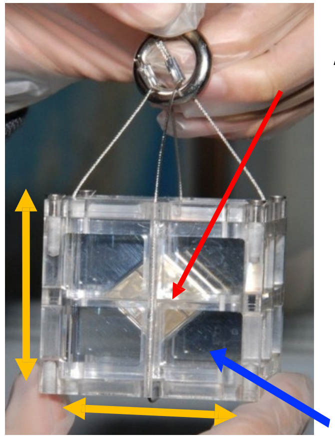
Confirmed Gd built up from the bottom of the tank

NIM-A 1027 (2022) 166248

Gd concentration check after loading

- Neutron capture time is sensitive to Gd concentration.

Am/Be neutron source was deployed in SK



8 BGO Crystals

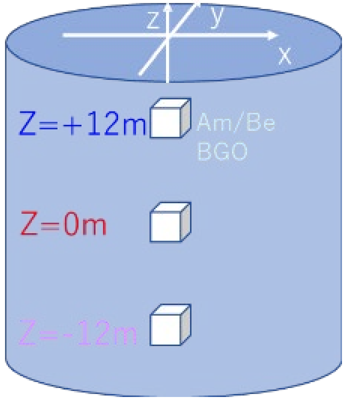
Am/Be neutron source

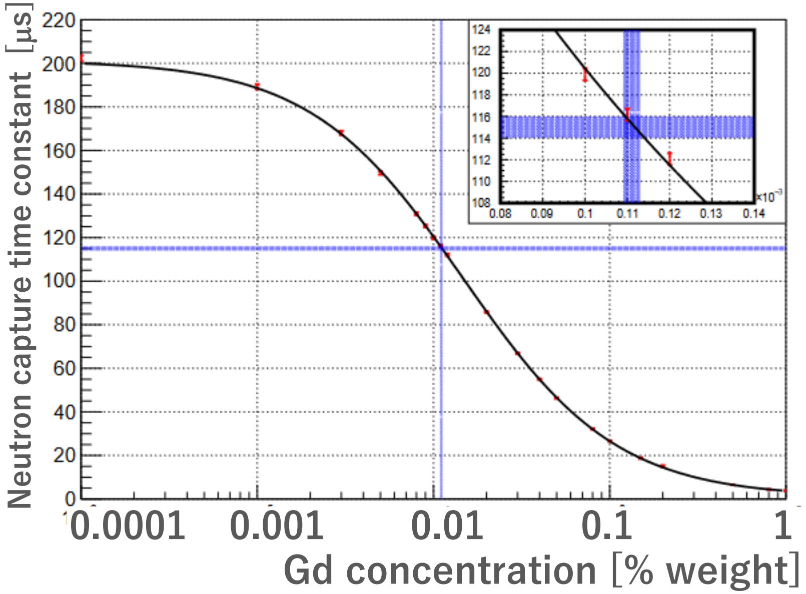
100~200 neutrons/s

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

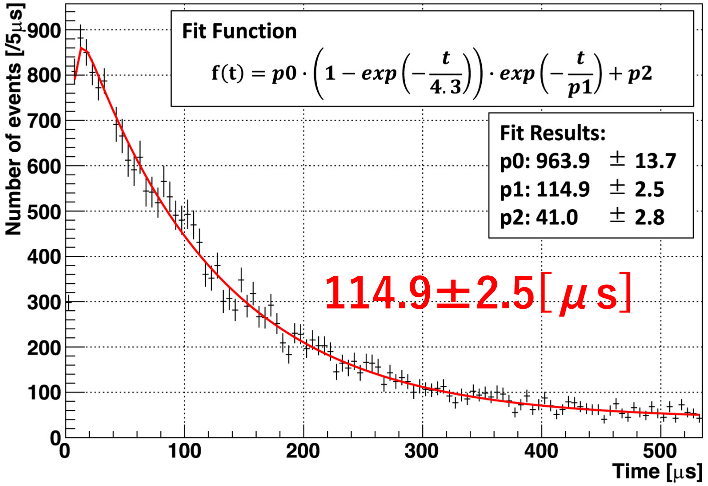
$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C}^{*} + \mathrm{n}$ (2-6 MeV)

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

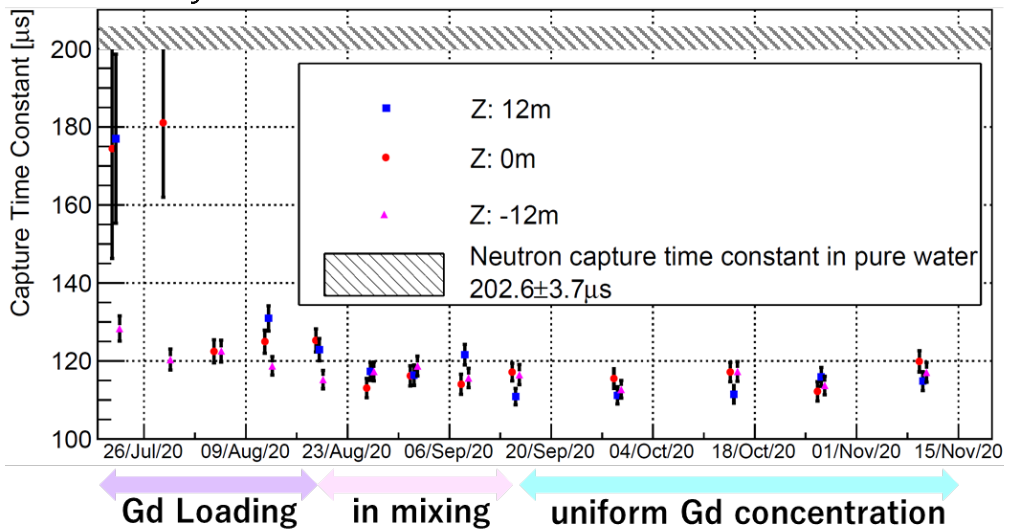




Time difference between scintillation and neutron capture γ-rays as of September 29, 2020



Every two weeks



Since September 2020:
The average capture time 115.6 ± 0.6 μs
=>Gd concentration 110.9 ± 1.4 ppm

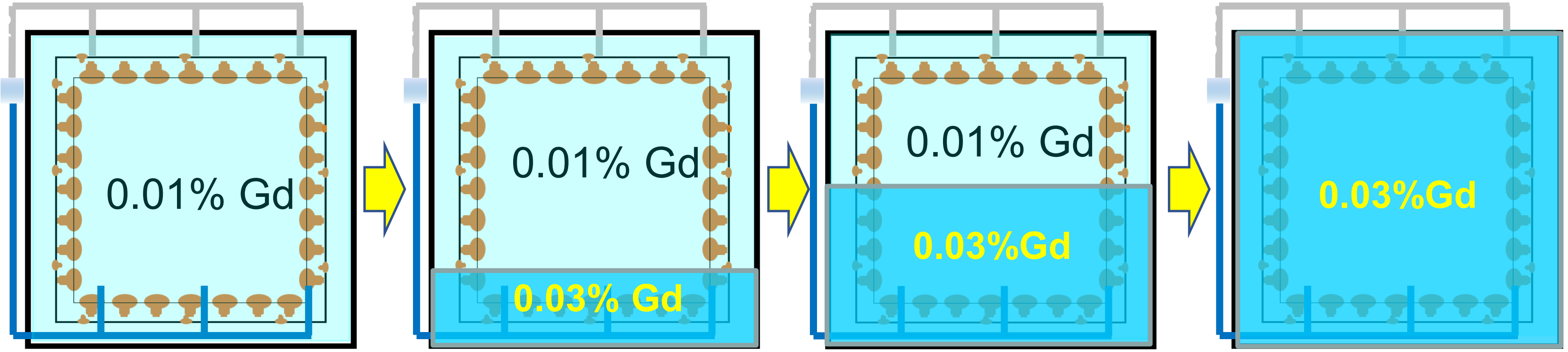
The 2nd Gd-loading Jun 1 – Jul. 5, 2022

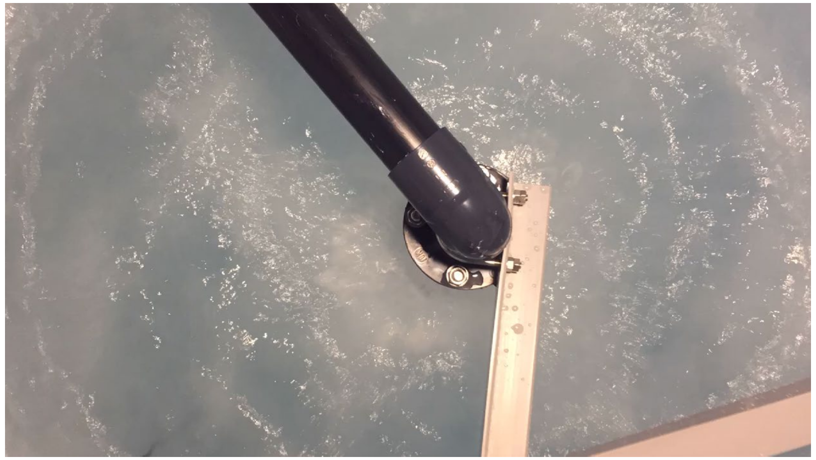
0.01% Gd water was taken from the top and returned from the bottom in **0.06% $Gd_2(SO_4)_3$** solution **(=0.03% Gd = 0.078% $Gd_2(SO_4)_3 \cdot 8H_2O$)**. It took 35 days to replace 50,000 tons of water at 60 m^3/h

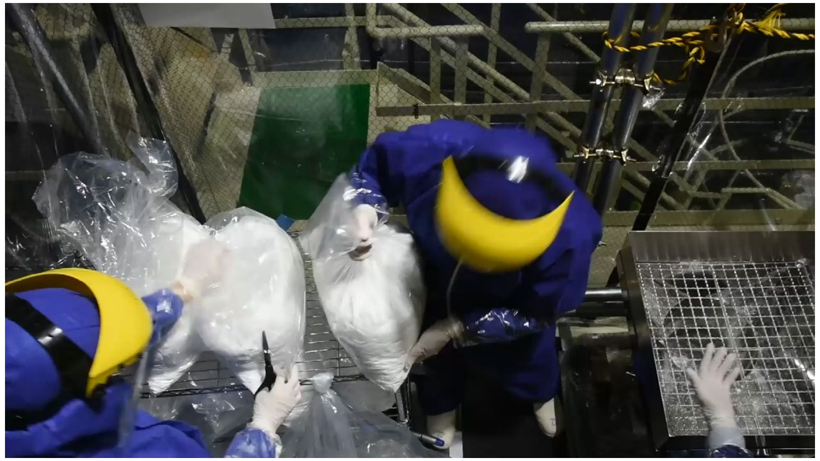
The doubled dissolving capacity

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

~900kg /day x 35 day







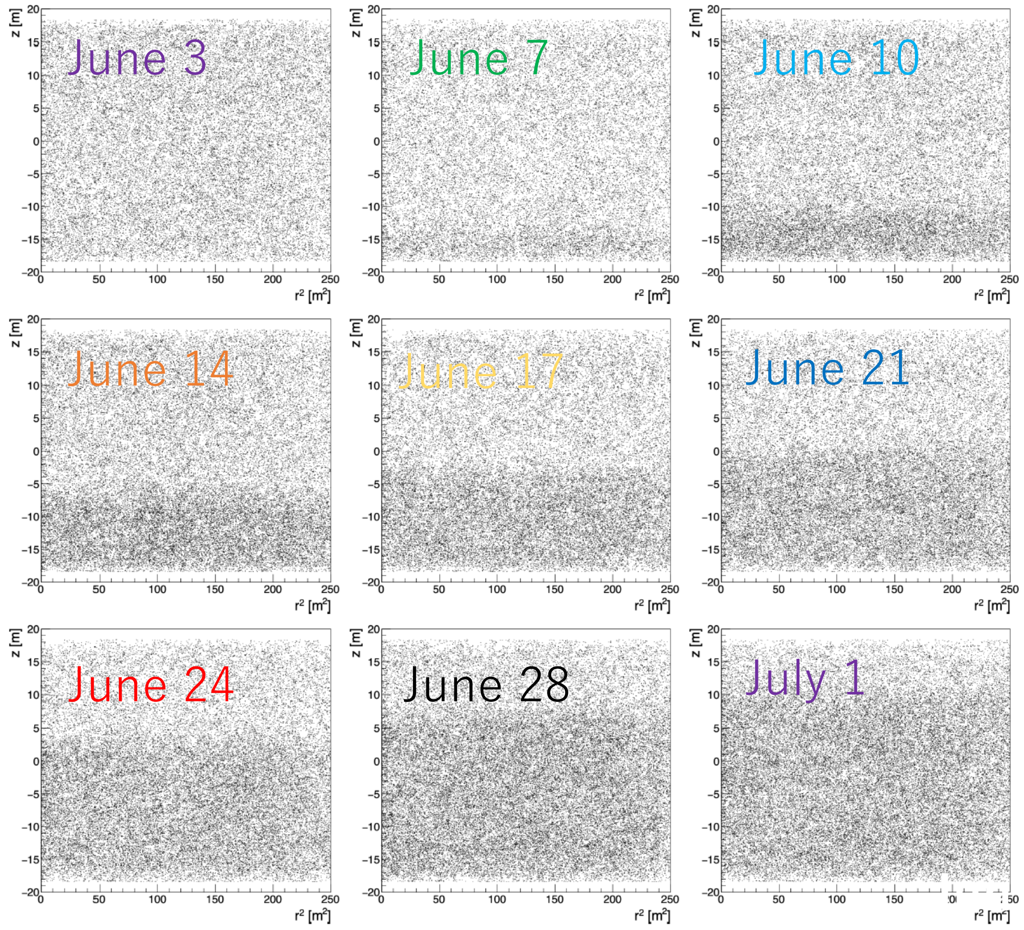
27tons
=1350 x 20kg cardboard boxes!

The 2nd Gd-loading

NIMA 1065 (2024) 169480

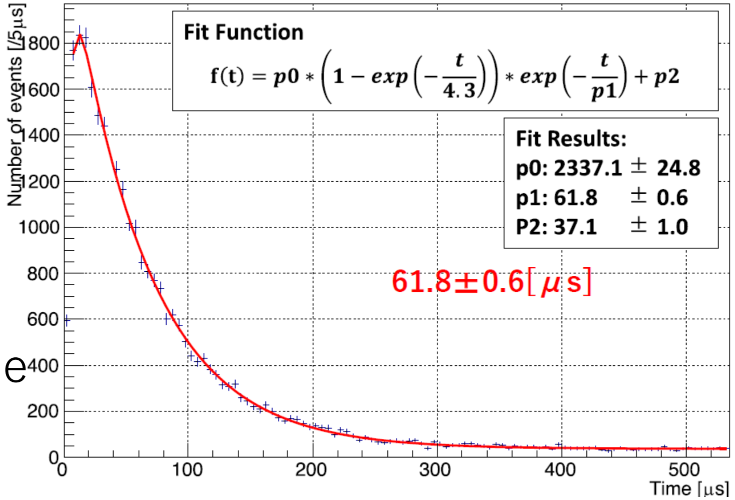
Am/Be neutron calibration
~310ppm was confirmed by the neutron capture time

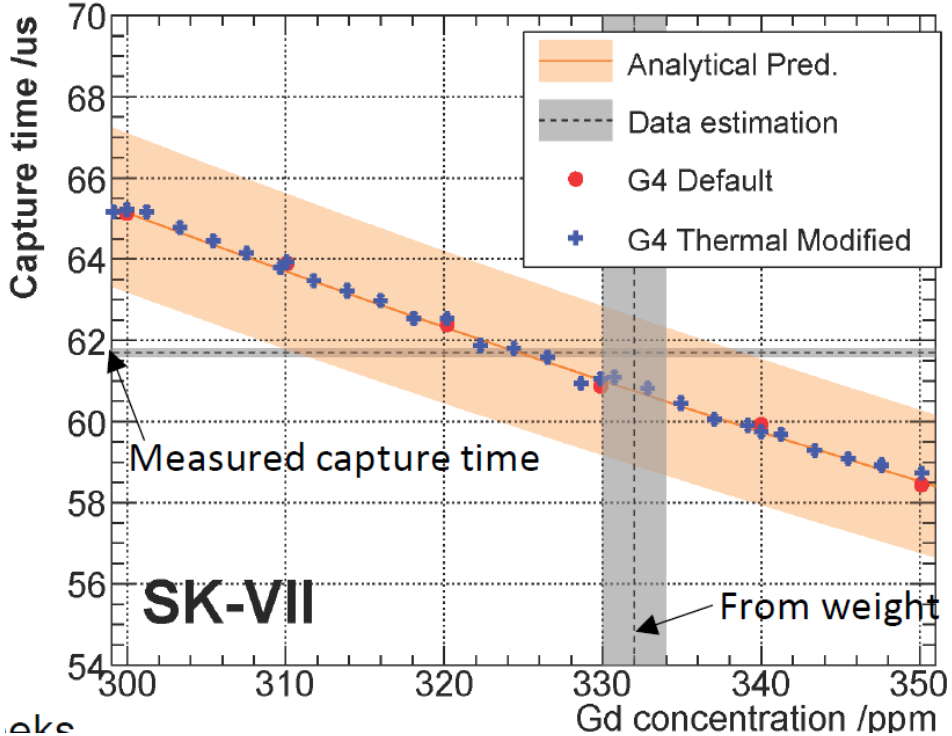
Spallation neutrons
1.5 times neutron capture efficiency was confirmed



Sep.28 2022
SK-VII (0.033%Gd)

Nuetron capture time





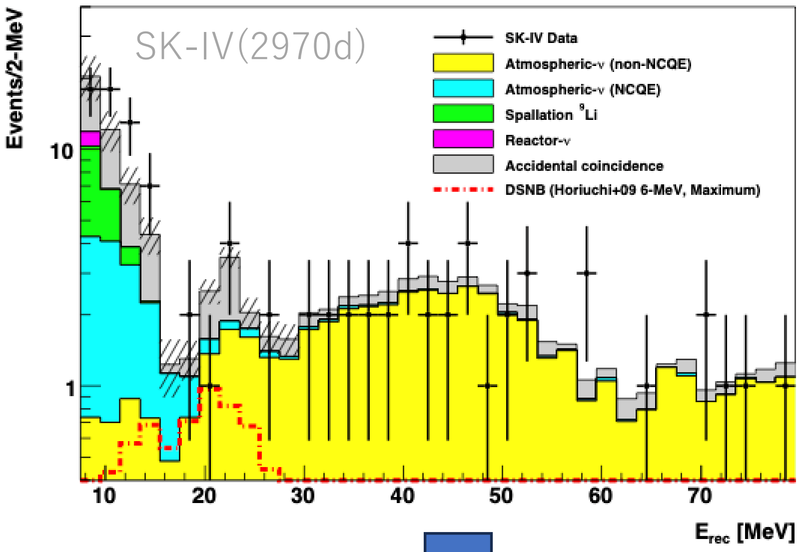
PTEP (2025) 013C01

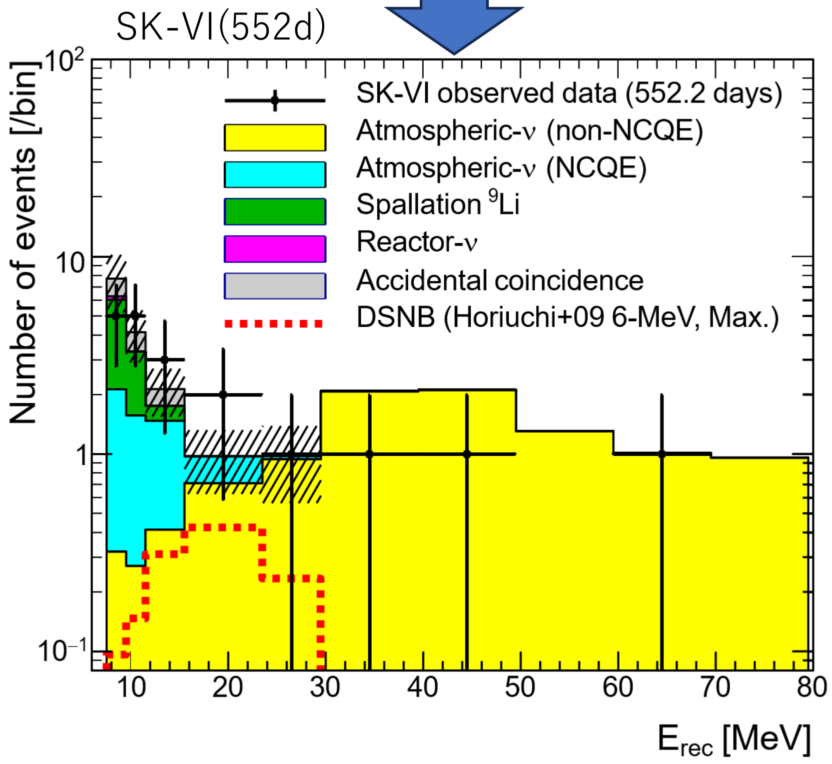
The first result of SK-Gd

ApJ. Letter 951, L27 (2023)

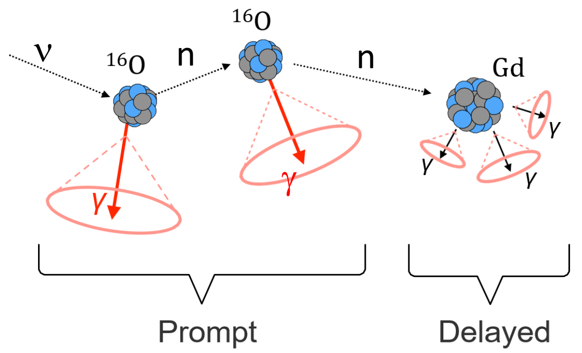
- Using conventional methods with 552 days of data from SK-VI, after the introduction of 0.01% Gd.

- Thanks to Gd, the accidental background was reduced significantly.



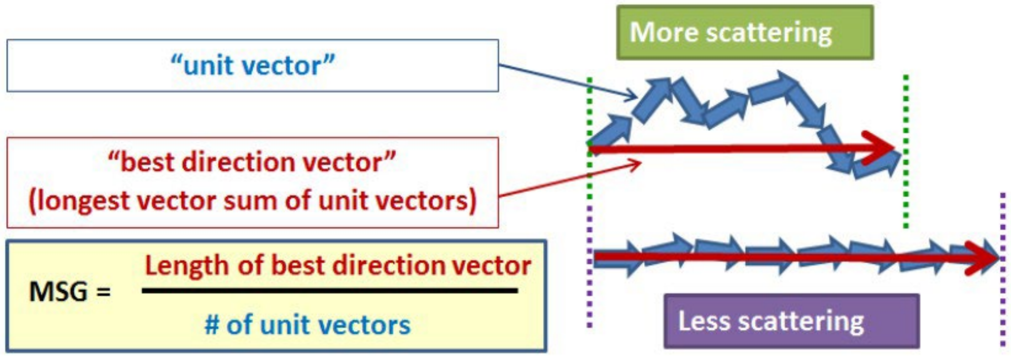


Analysis improvement: Atmospheric ν NCQE reduction



If multiple gamma rays of the prompt events are identified, they can be reduced.

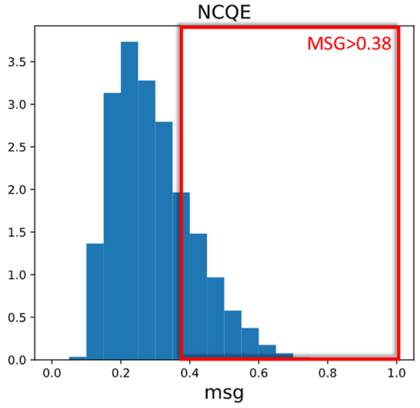
- **Multiple scattering goodness (MSG)**
  - A parameter developed to reduce low-energy background (BG) in solar neutrino analysis.



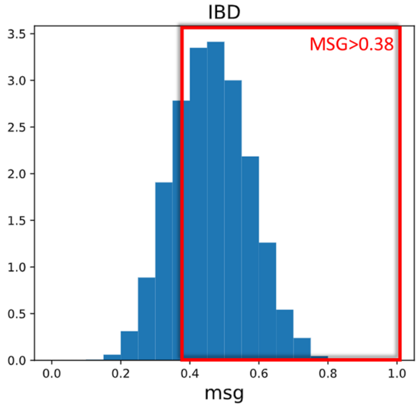
A smaller MSG:
A more isotropic hit pattern:
More NCQE-like.

A larger MSG:
A more forward-oriented hit pattern:
More IBD-like.

NCQE



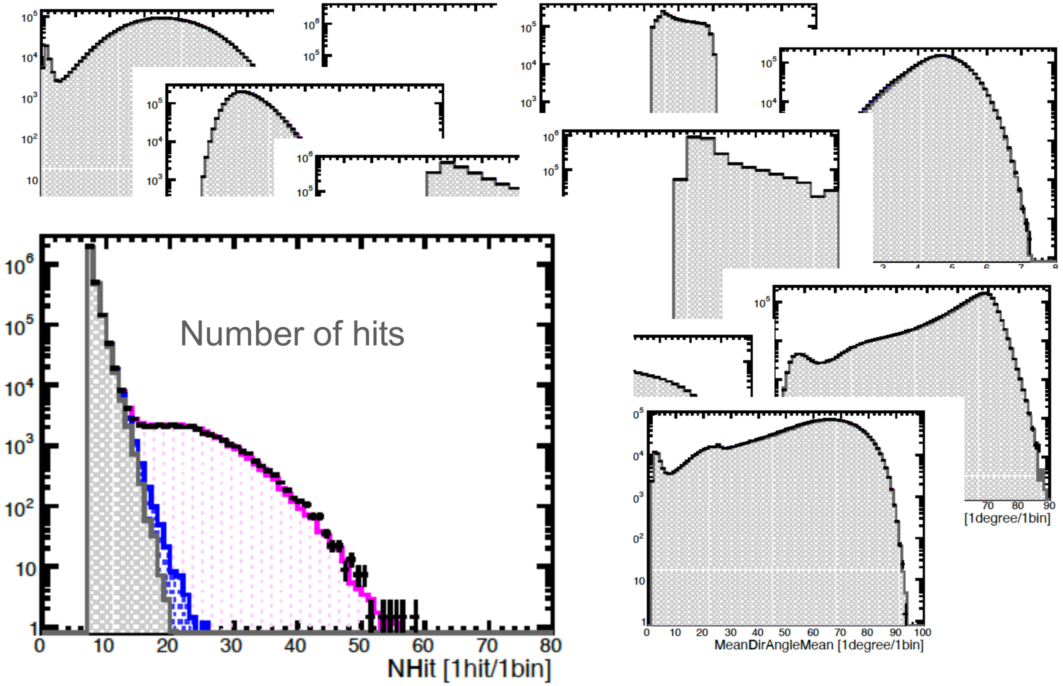
IBD (signal)

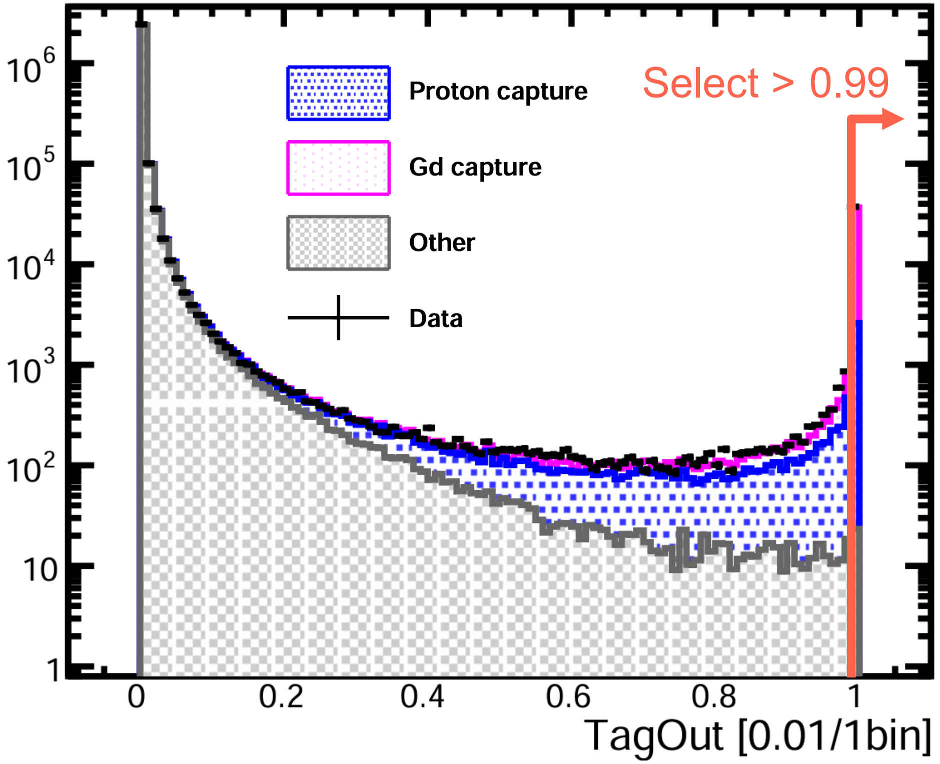


Analysis improvement: ML-based neutron-tagging

- **Neutron tagging using Neural Network**

12 Feature variables



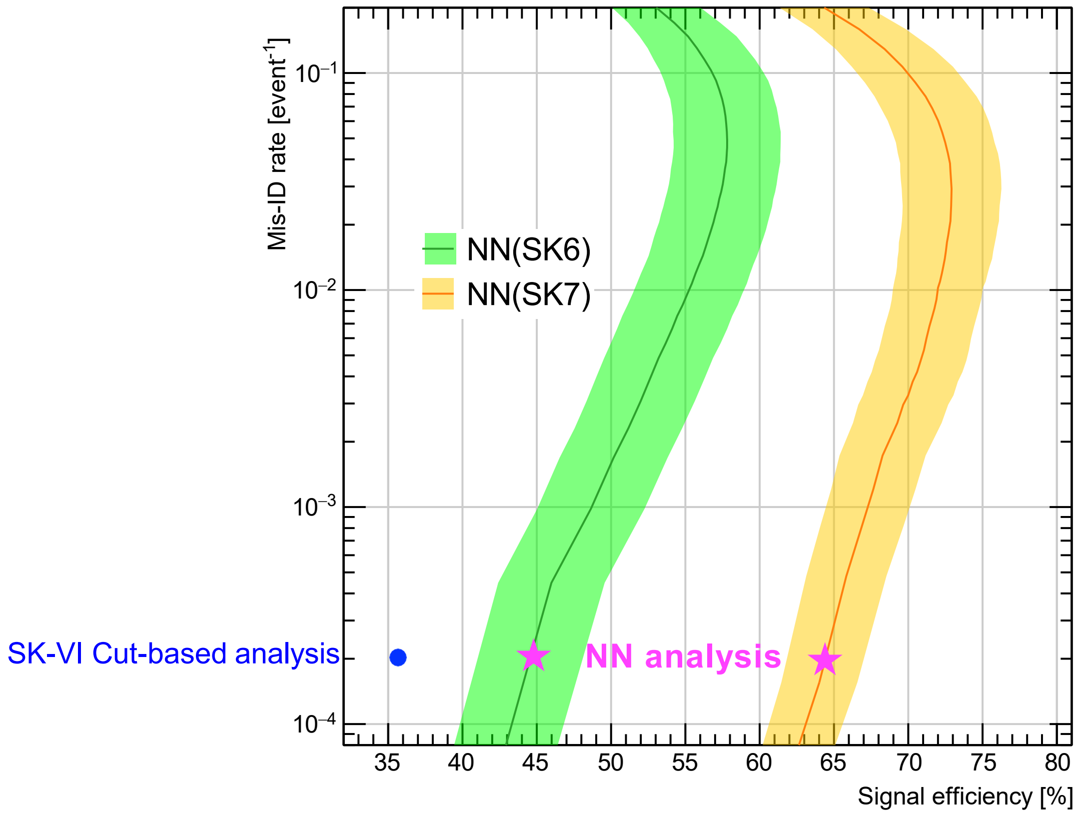


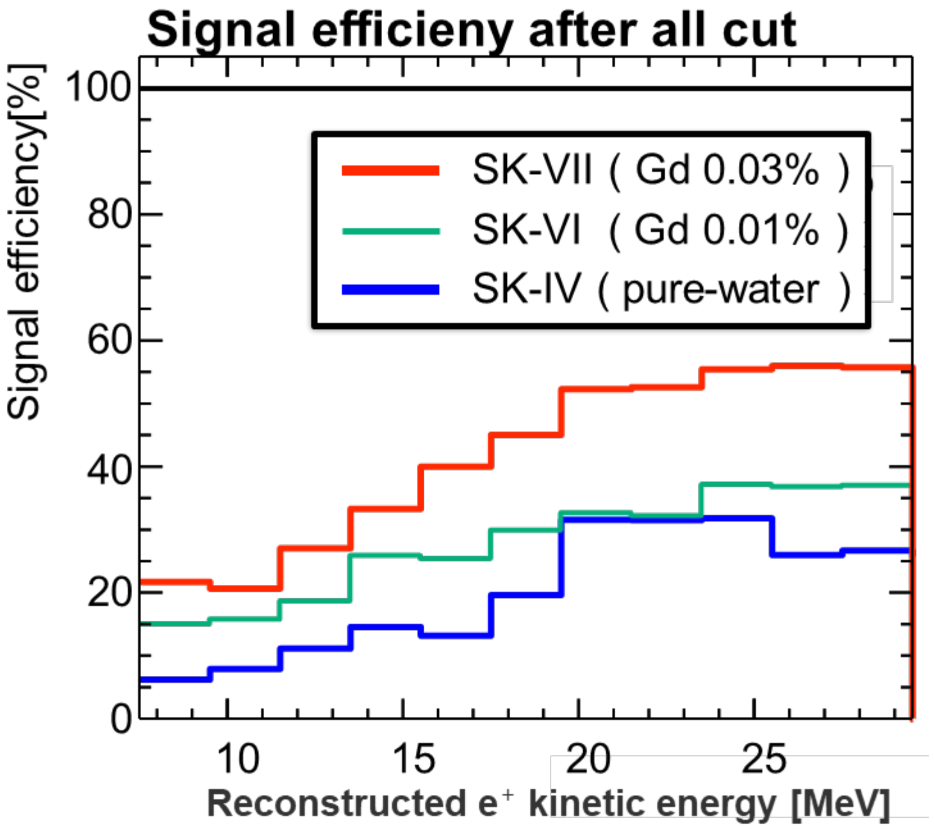
SK-VI: 45.4±3.9% with 0.02% mis-ID

→1.3 times better than the Cut-based analysis

Analysis improvement: ML-based neutron-tagging

- Neutron tagging using Neural Network





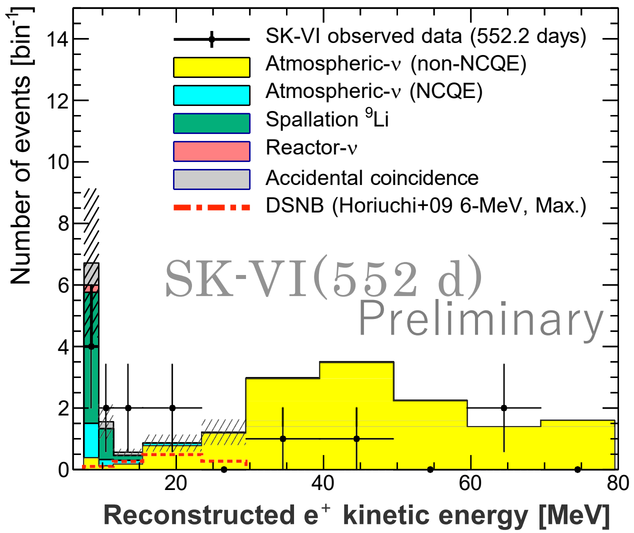
The efficiency is significantly improved!

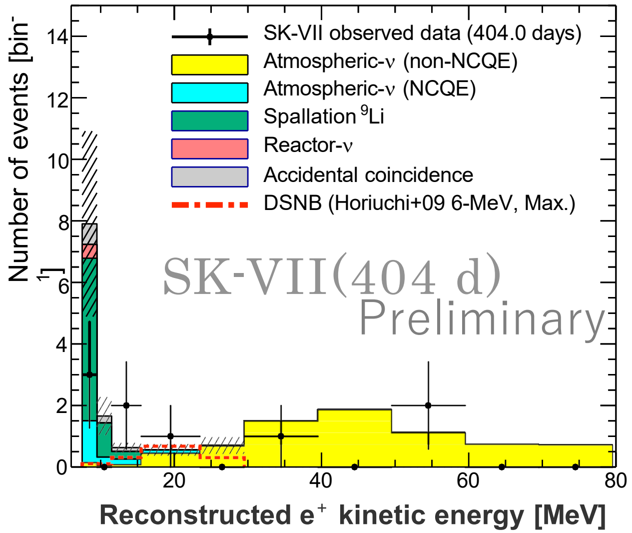
SK-Gd(0.01% 552.2d+0.03% 404d)

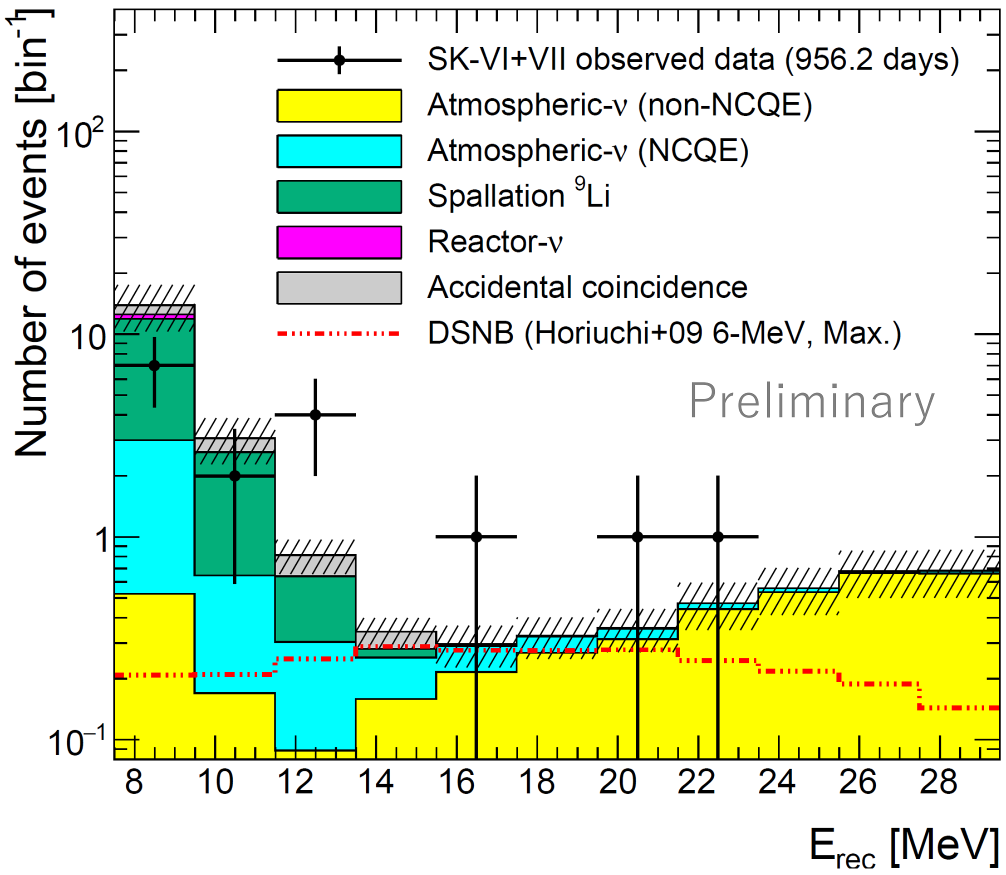
Neutrino2024 Harada

w/ New NCQE reduction cut

ML 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

Borexino 2771 days Observed 90% C.L. (Astropart. Phys. 2021)

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

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

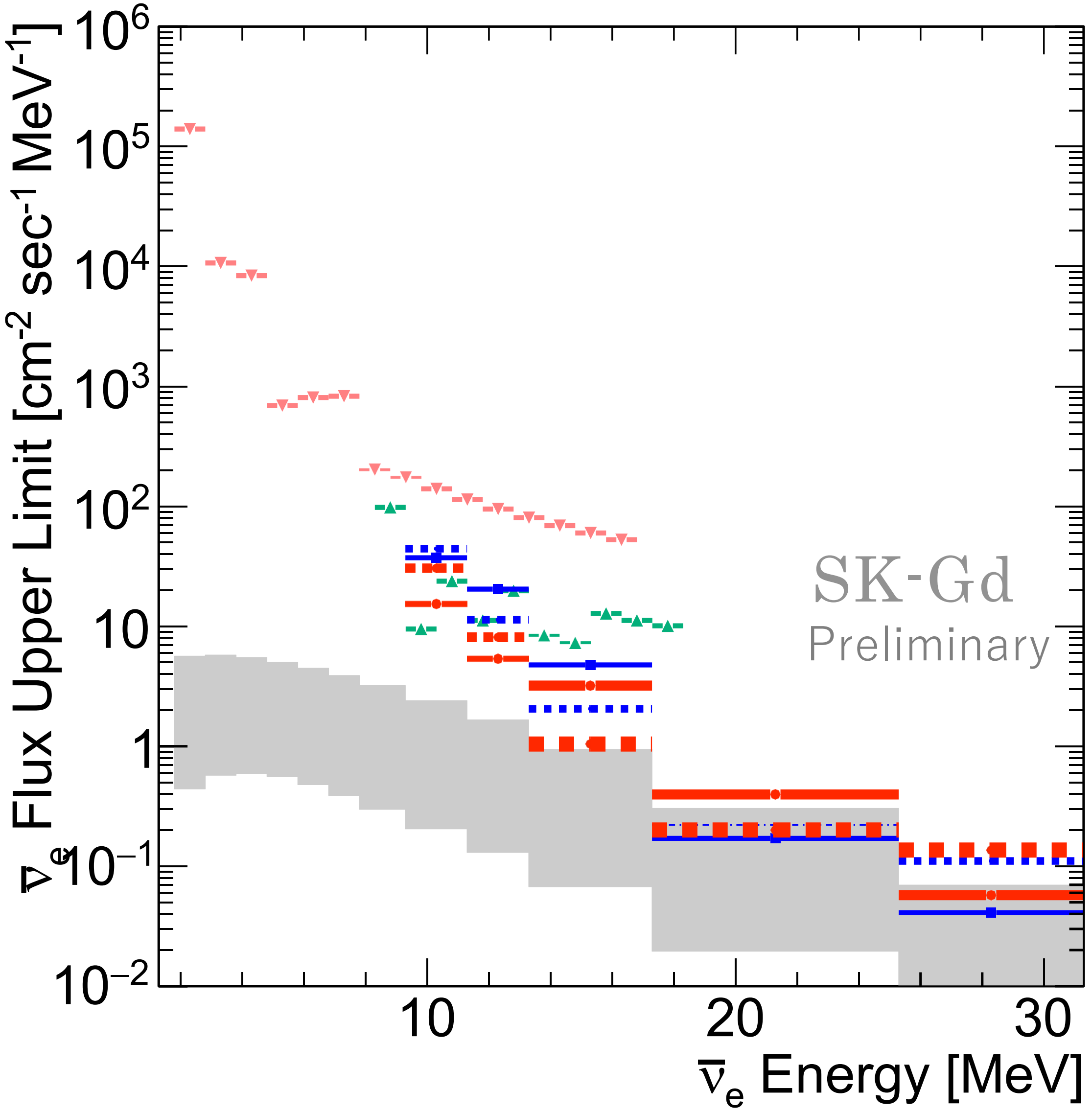
SK-VI+VII 956.2 days, 90% C.L. sensitivity (New)

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

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

Modern DSNB Theoretical Predictions

Neutrino2024 Harada



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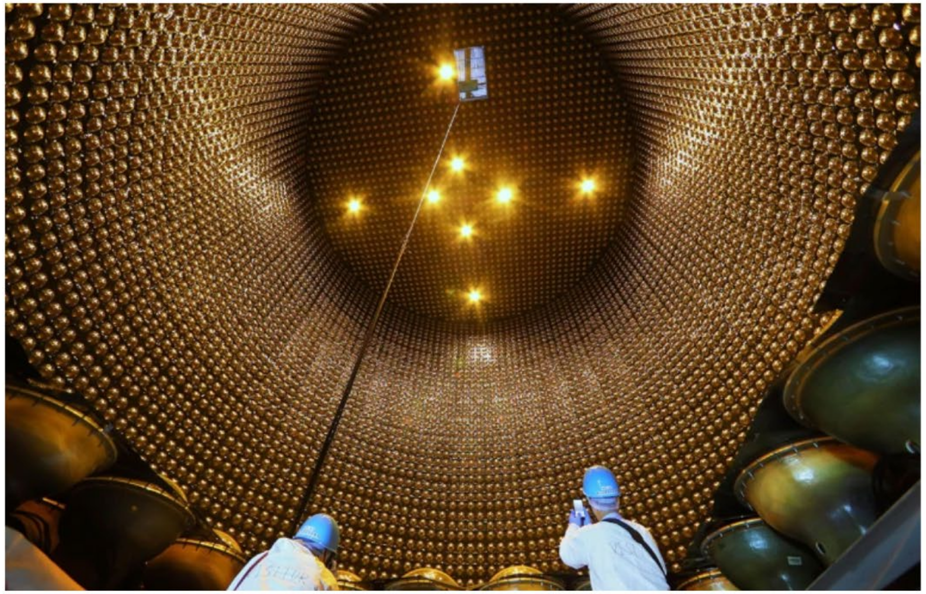
NEWS | 09 July 2024

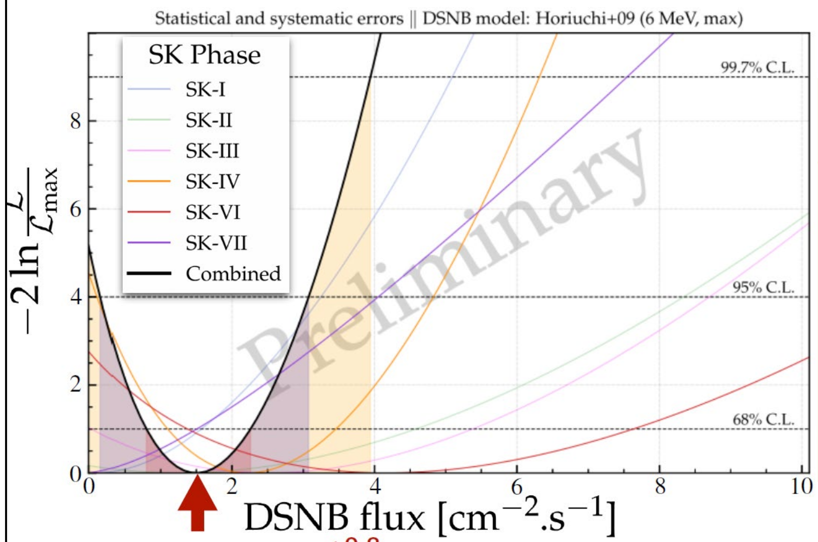
Huge neutrino detector sees first hints of particles from exploding stars

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

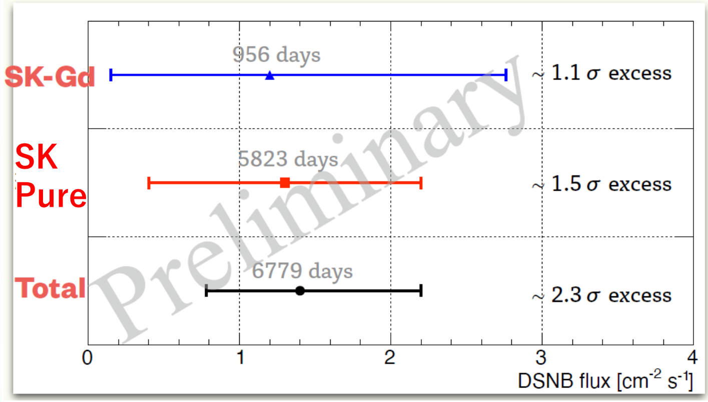
By Davide Castelvecchi



Hints ?



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



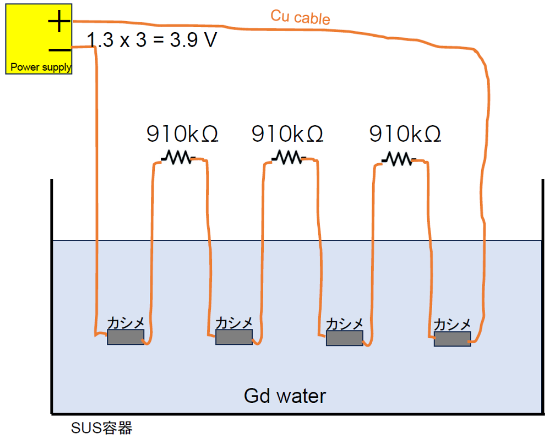
Rejecting the zero DSNB hypothesis at 2.3σ

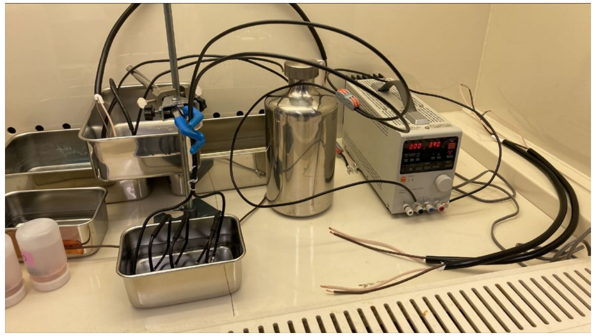
SK 6779 days of data
(5823 days of pure water and 956 days of Gd water)

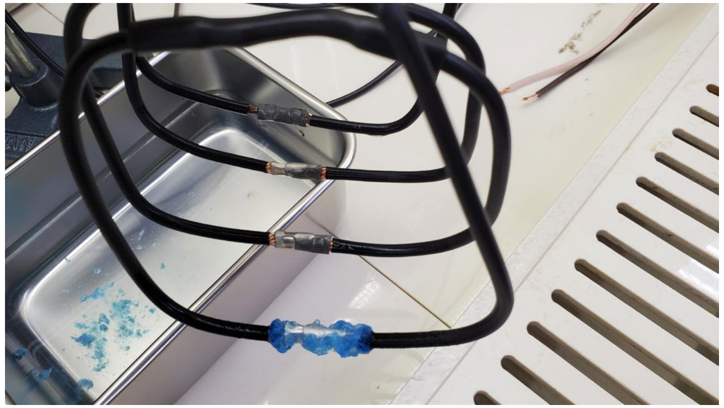
Lowering the analysis threshold while advancing the understanding of atmospheric neutrino background through T2K, aiming for discovery.

More challenges still lie ahead.

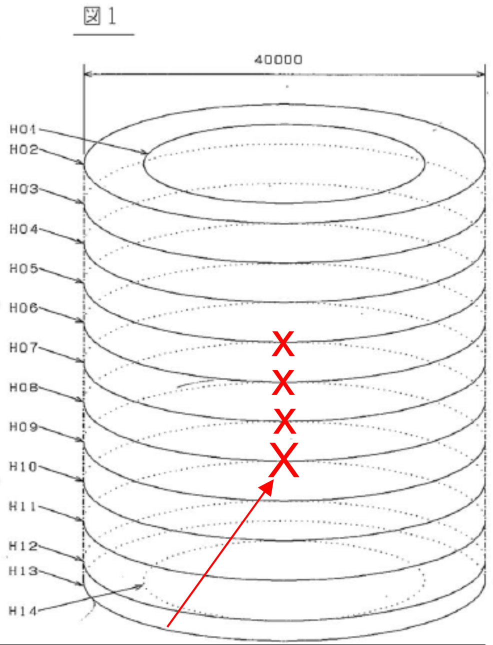
If the insulation of a cable is damaged and the copper is exposed, it can dissolve when submerged in a gadolinium sulfate solution.

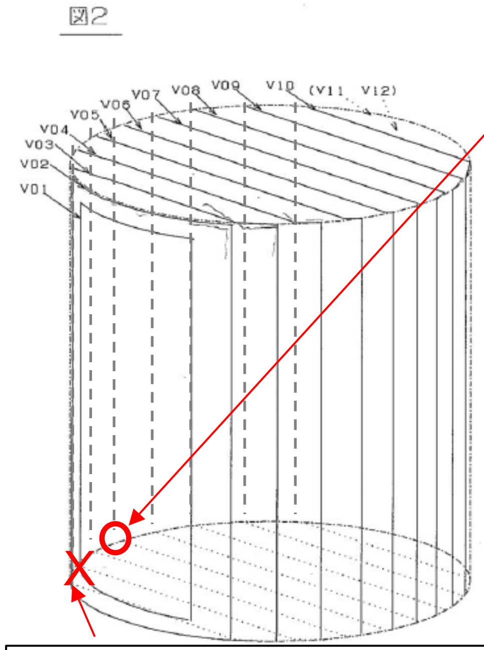






SK's geomagnetic compensation coil problems and countermeasures



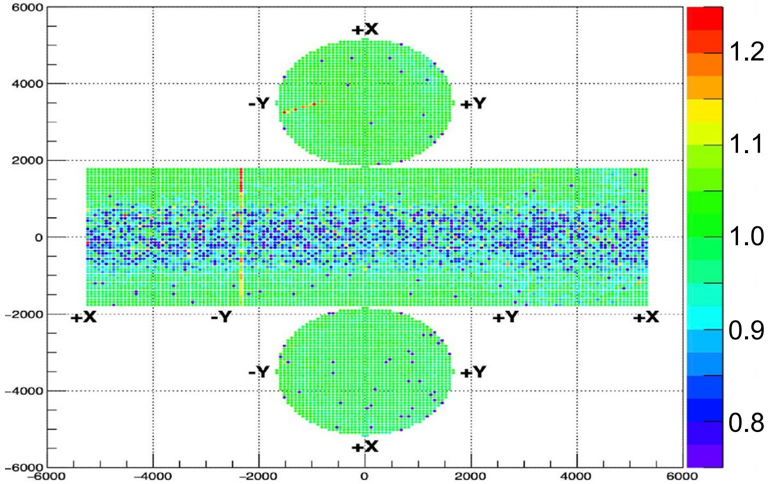


V06 disconnected on Oct.25, 2023.
Damaged sub-cable was bypassed on Dec.1, 2023. [recovered]

H09 disconnected on Dec.8, 2023.
Due to power supply configuration, H06, H07, and H08 are also off.

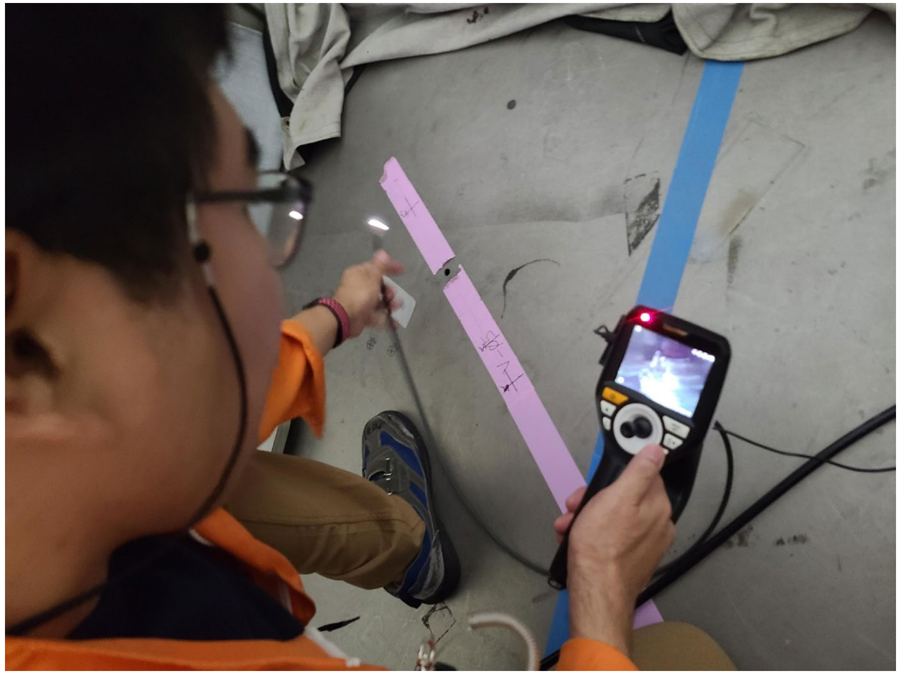
V01 disconnected on Nov.15, 2023.
V01 was bypassed from the power supply on Dec.2, 2023.

PMT photoelectron collection efficiency ratio, comparing May 2024 condition to nominal



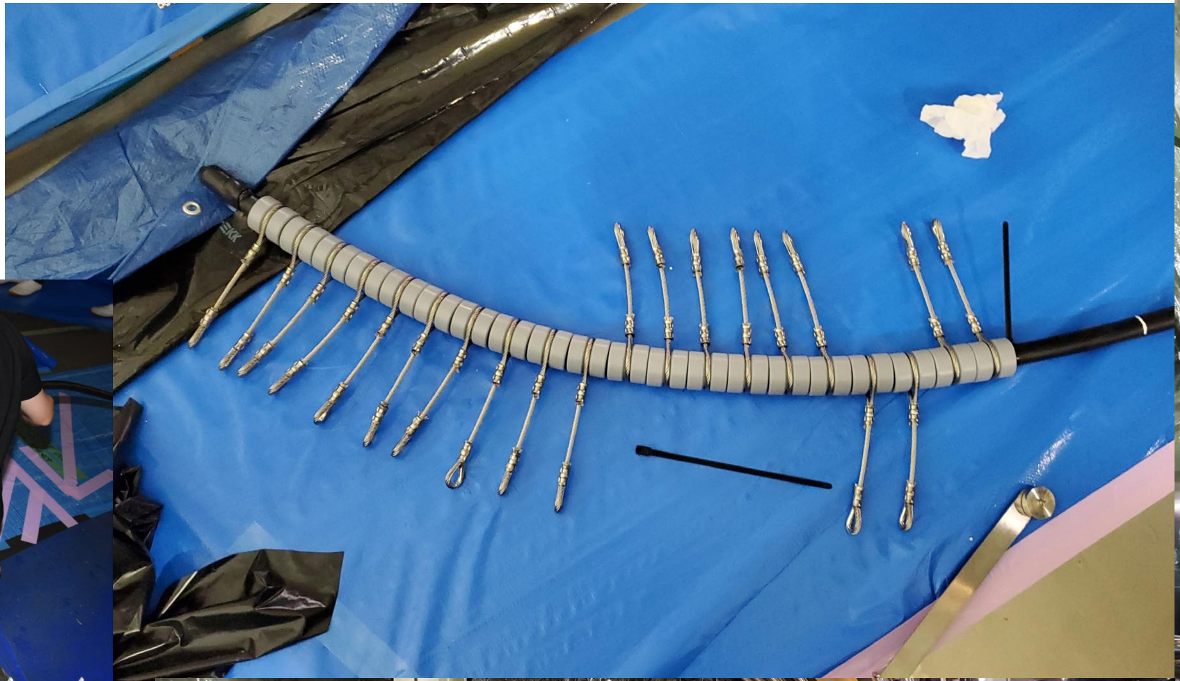
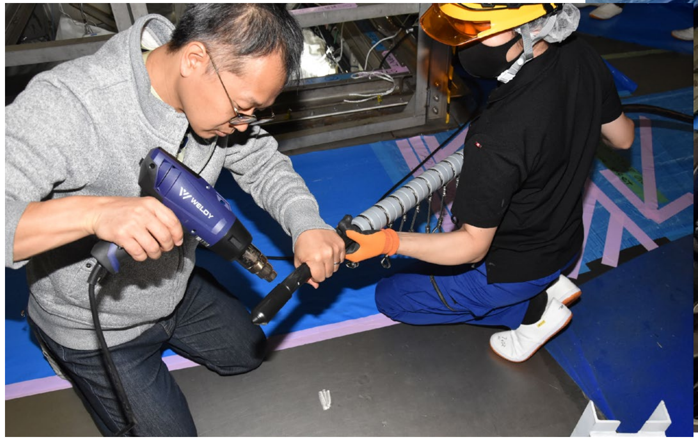
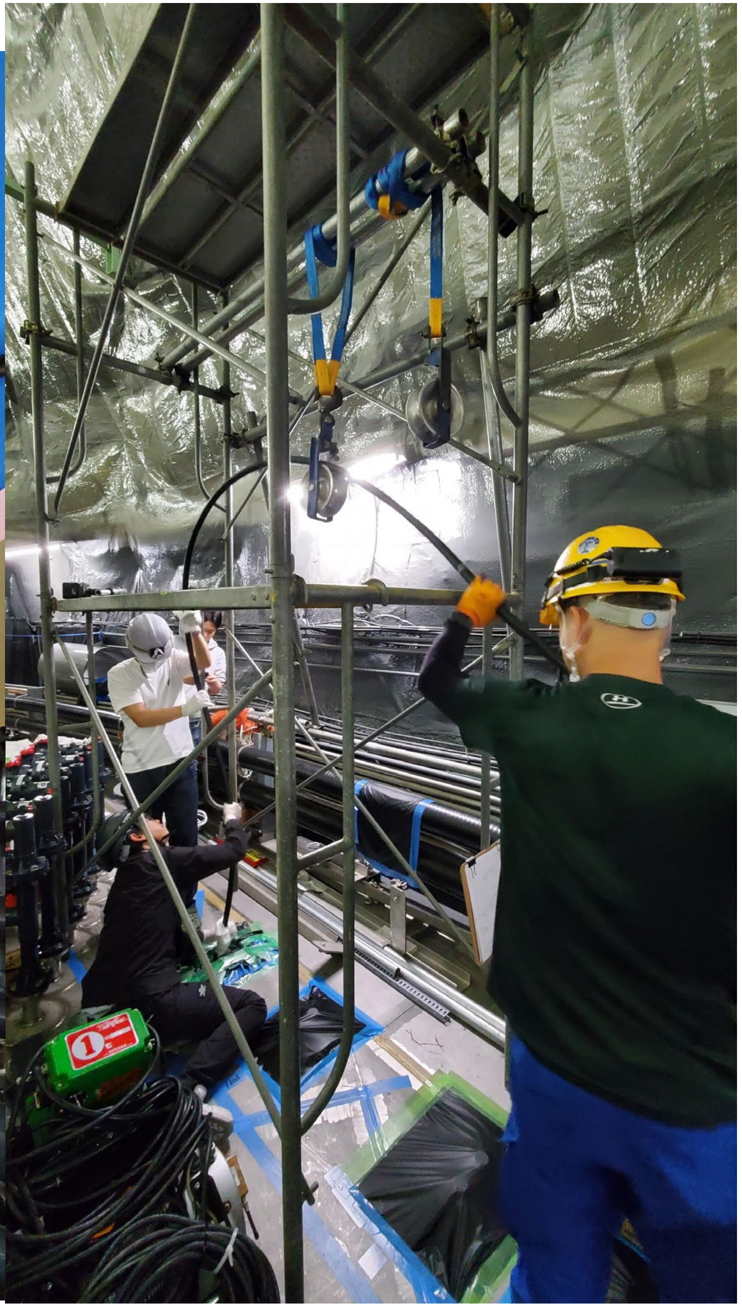
- SK geomagnetic compensation coil cables have failed in three locations.
- At two of locations, part of the coil was successfully bypassed to restore functionality. The other location is entirely underwater, resulting in the entire cable group being turned off.
- A 10-20% decrease in collection efficiency is observed for about 20% of PMTs in the barrel.
- Efficiency for detecting neutron capture on Gd has also decreased by about 3%.
- The physics impact can be compensated by calibration and simulation.
- The likely cause is corrosion of wire connections due to ionized water seeping in under heat shrink insulation.
- SK plans to install six new horizontal coils in summer 2024 to restore the geomagnetic field cancellation.

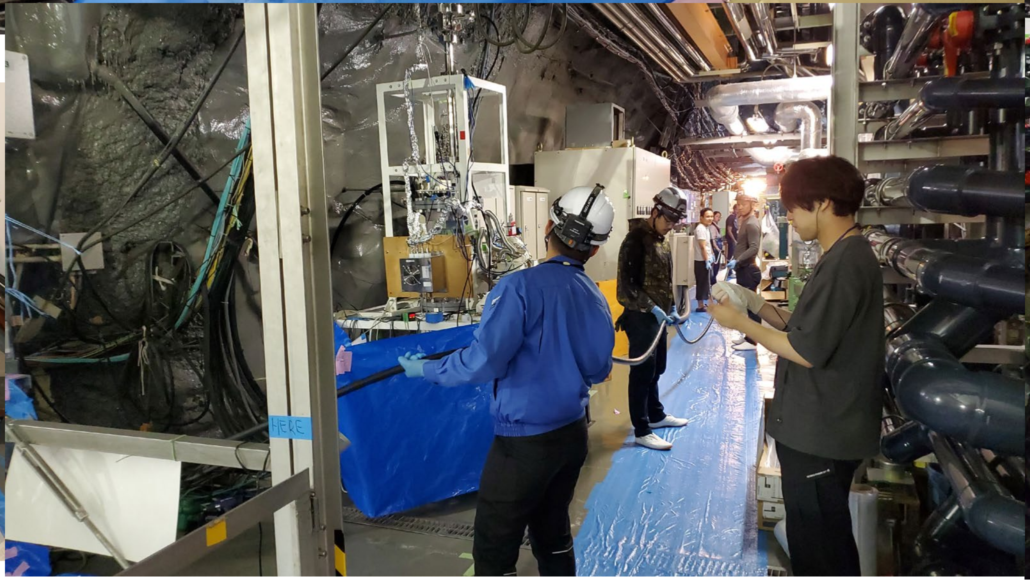
For vertical coils



Coil repair work

- 2024 June-September



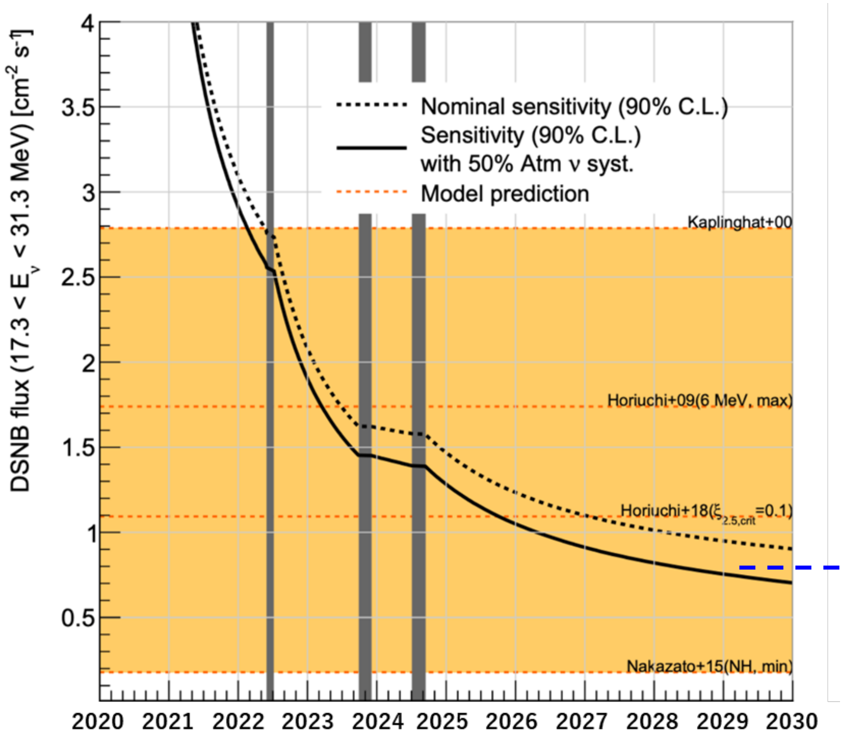

a14


a14

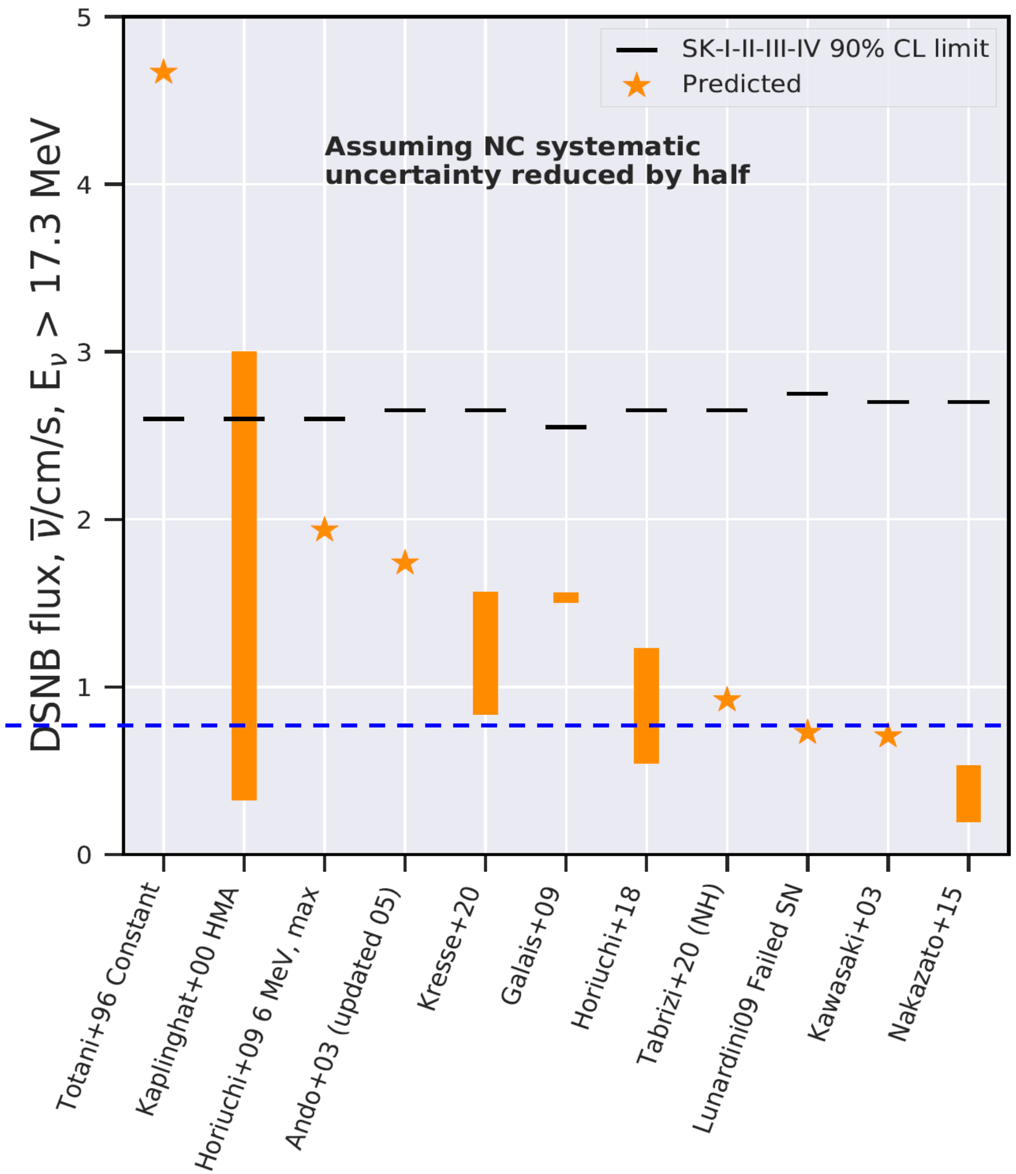
SK's DSNB search prospects

Sensitivity 90%CL

M. Harada



During the period when Coil #3 was broken, the 'SK7.5' phase lasted for 216 days (150 days live time), assuming the same efficiency as SK6."

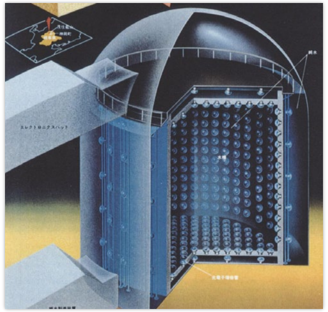


Super-Kamiokande
Phys. Rev. D **104**, 122002 (2021)

March 2029

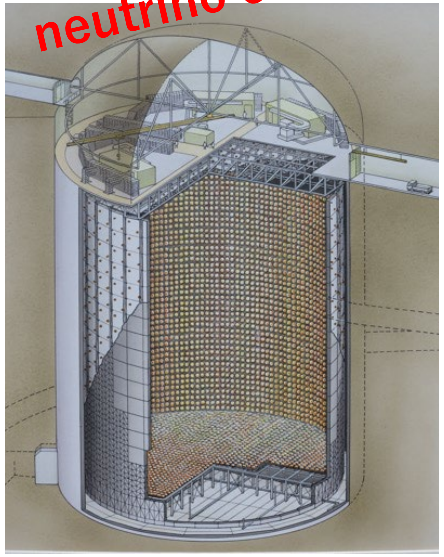
The 3rd generation of "Kamiokande"

First observation of supernova neutrinos

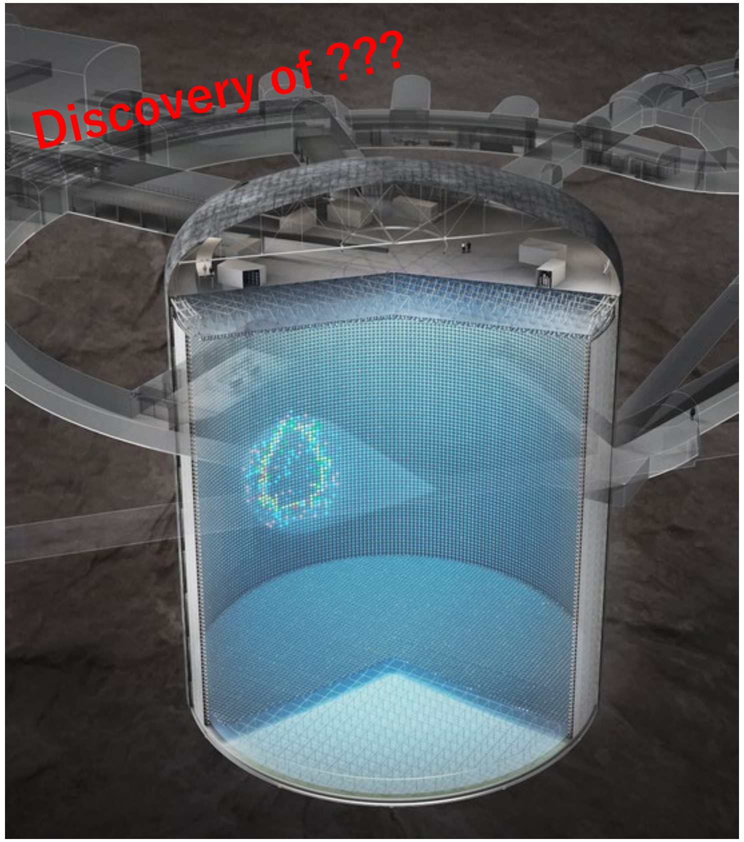


Kamiokande
Φ16 m × H16 m
0.7-1 kton / 3 kton
1k 20'' PMTs
1983-1996

Discovery of the neutrino oscillation



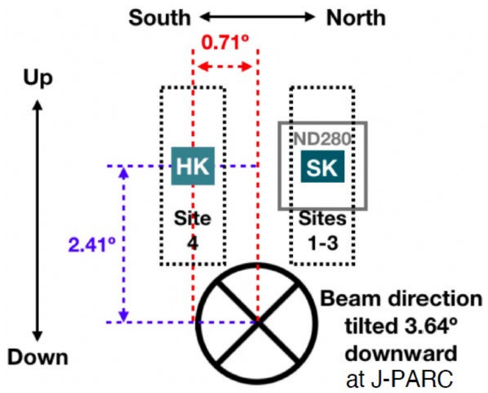
Super-Kamiokande
Φ41 m × H40 m
22 kton / 50 kton
11k 20'' PMTs
1996-ongoing



Hyper-Kamiokande
Φ68 m × H71 m
186 kton / 260 kton(~8 x SK)
20k 20'' High QE, T res. PMTs
(2 × SK's performance)
2028 ----> 20yers

Hyper-Kamiokande site

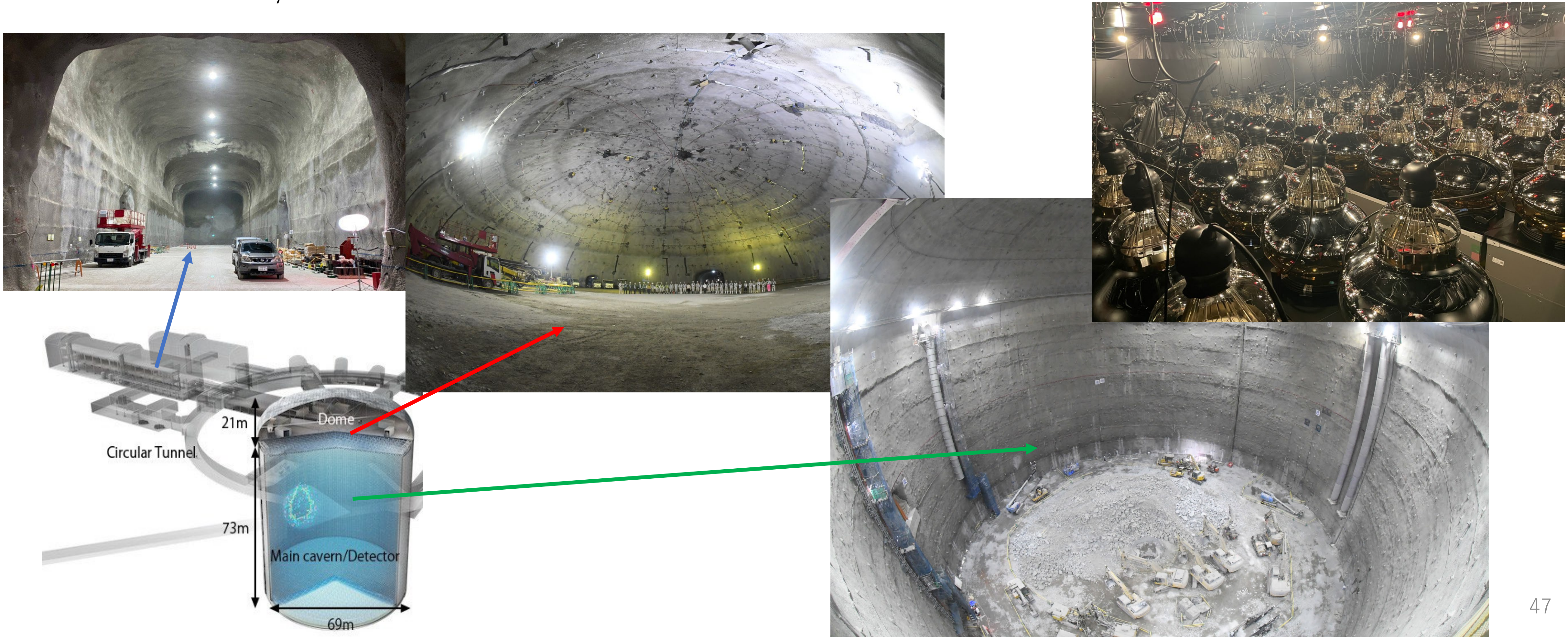
- 8 km south of Super-K
- 295 km from J-PARC and 2.5 deg. off-axis beam (same as Super-K) 13km depth
- 600 m rock overburden



12

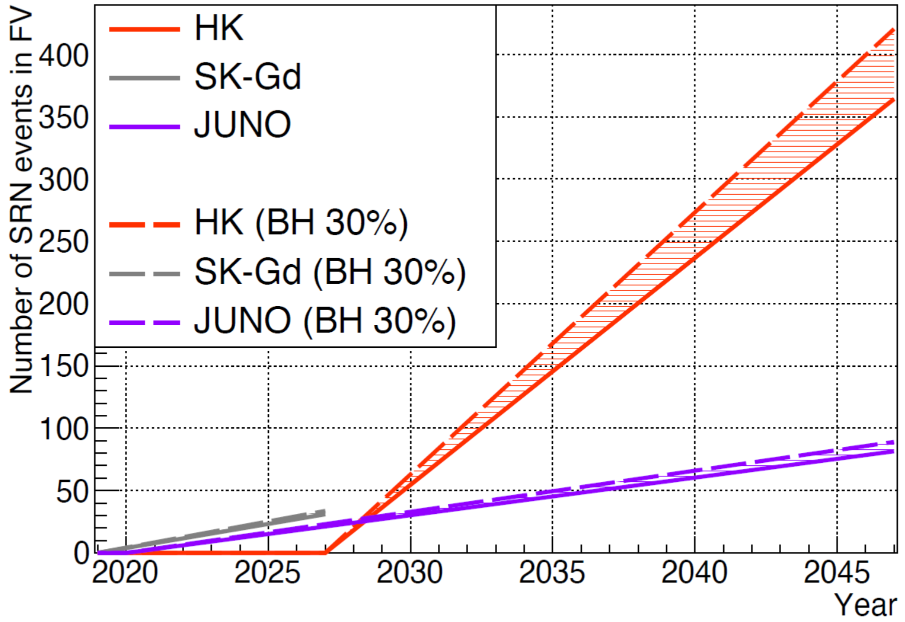
Hyper-Kamiokande Status

- Excavation of the dome part and the cavity for the water system completed in 2023
- Barrel excavation ongoing, and tank construction will be started soon.
- As of Feb. 2025, 13271 x 50cm PMTs are there! > SK’s 11129 PMTs

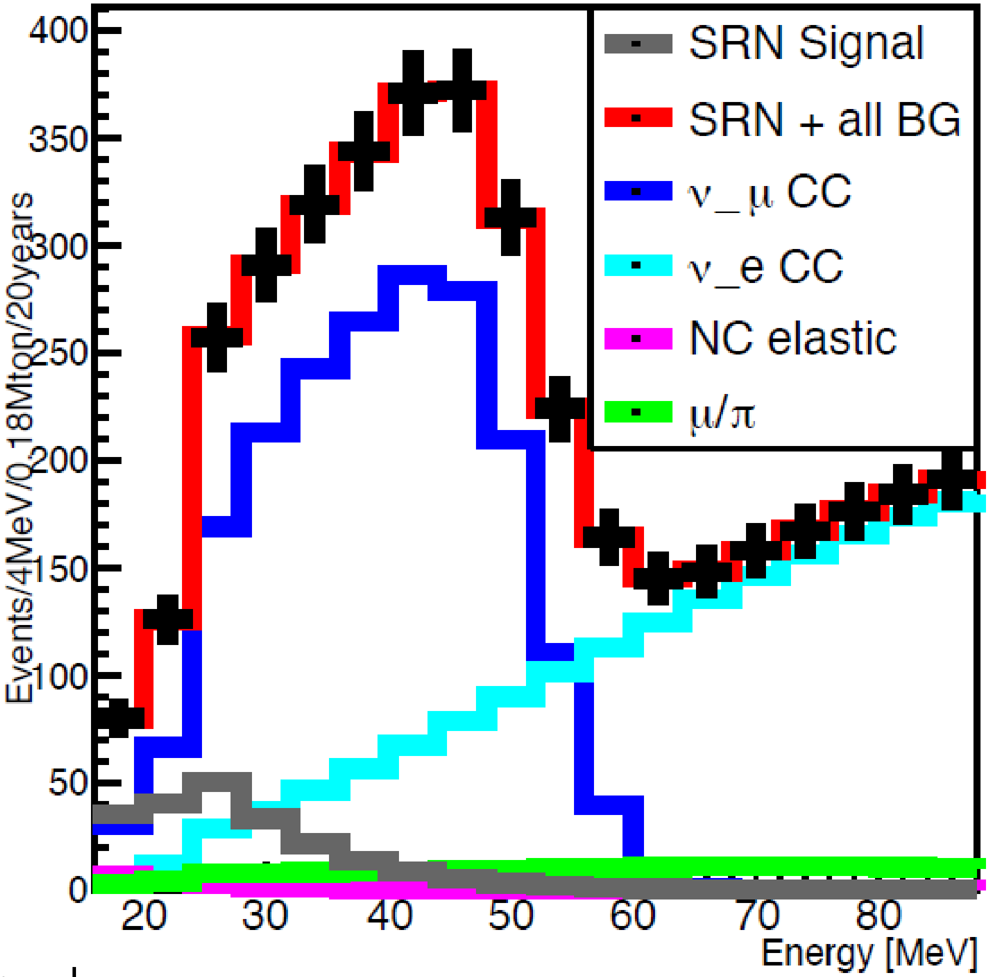


HK’s DSNB search for 20 years

Hyper-Kamioaknde Design Report arXiv:1805.04163



Middle angle (38-50°)



Assumptions

- No neutron tagging
- Energy > 19 MeV, where the impact of spallation background is small
  - Cut performance: Spallation BG=0, while signal efficiency 19-25MeV 54%, >25MeV 100%

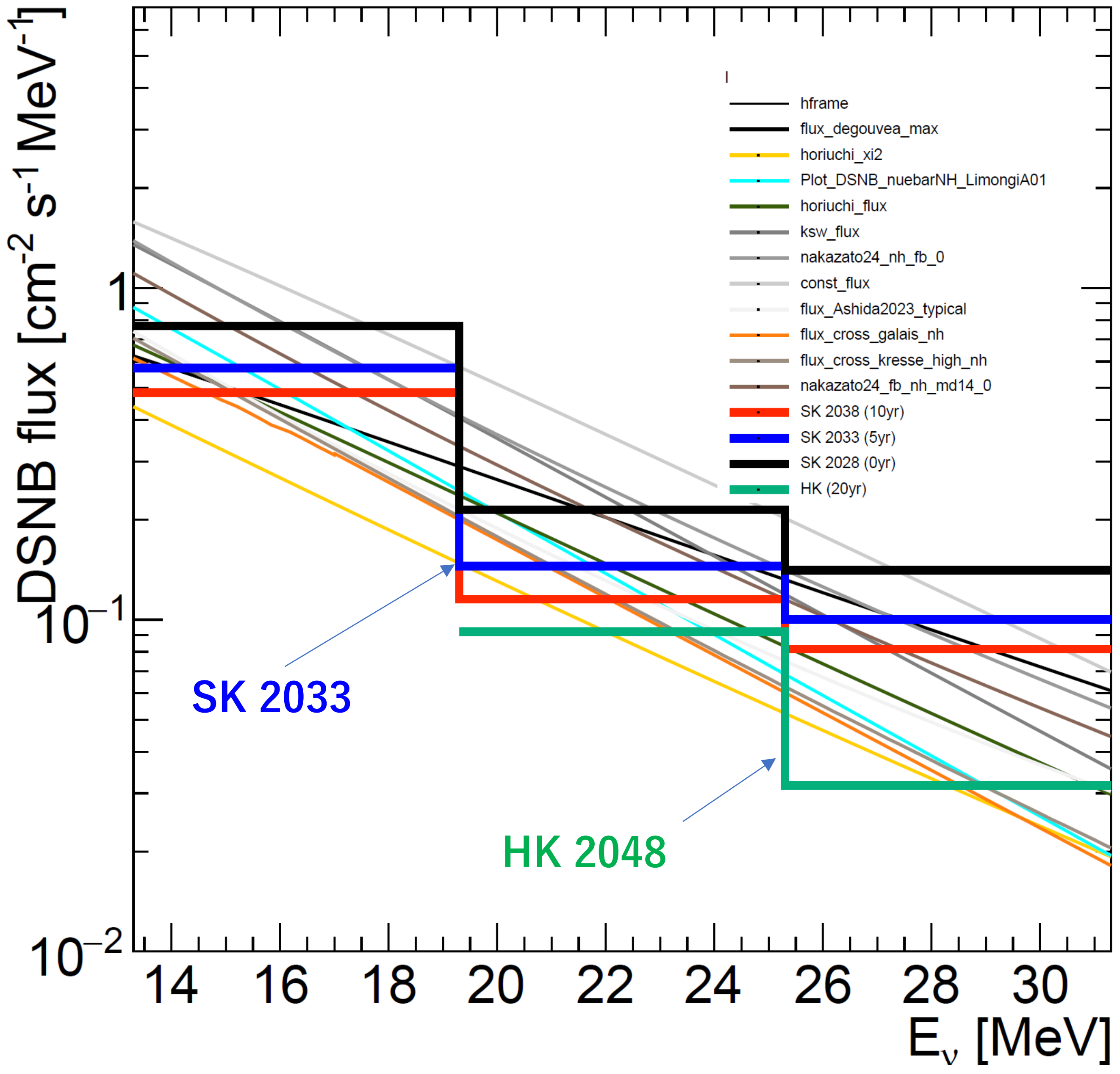
3σ Sensitivity

M. Harada

- Sensitivity at 3 σ, to model discrimination/parameter estimation

- SK FY2028 + 0 y
- SK FY2028 + 5y(FY2033)
- SK FY2028 + 10y(FY2038)
- HK FY2028+ 20y(FY2048)

Based on HK design report



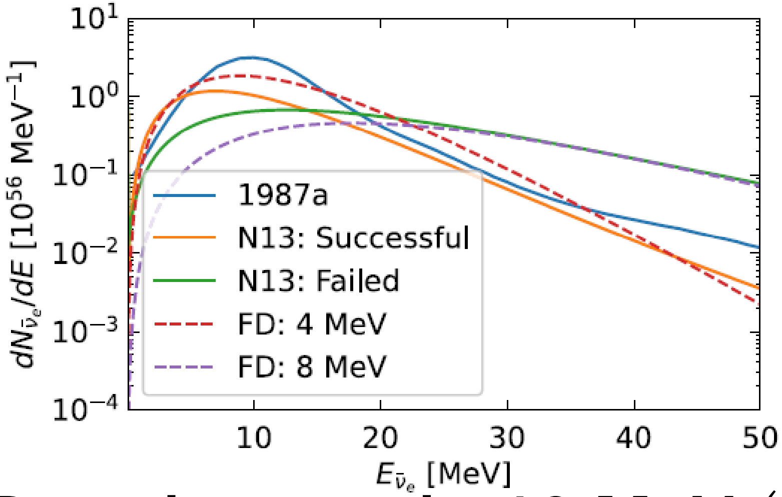
Assuming an early 3 σ detection at SK or HK

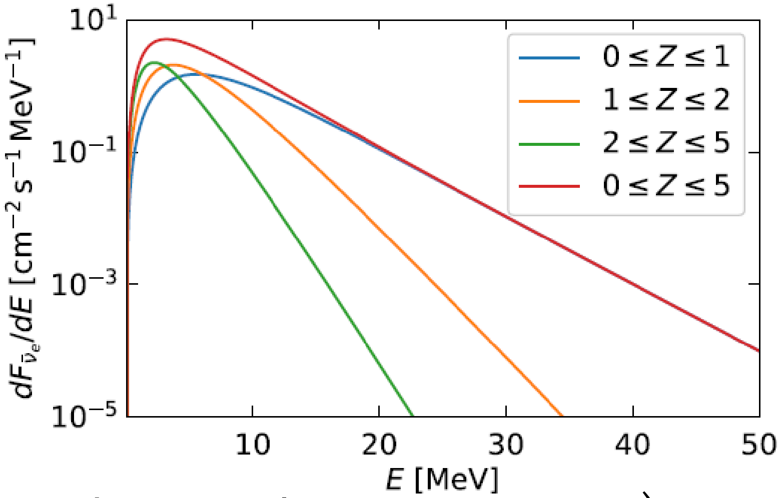
S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

Test models?

Volume or threshold?

Yudai Suwa





- If we can **capture the DSNB peak around ~10 MeV** (the thermal component), we may be able to place constraints on the star formation rate (SFR). In other words, we could infer the frequency of massive star deaths up to around redshift z ~ 2.
  - This could also provide a way to probe the initial mass function (IMF) in the early universe.
- The **power-law region above ~20 MeV** does not, by itself, allow us to determine any overall quantities. However, with a large statistical sample, dividing the data into two energy regions may allow us to measure the spectral hardness.
  - This highlights the importance of low-energy observations with Super-Kamiokande (SK).
  - Such information can help constrain whether the emission is purely thermal, or if it includes a power-law component resulting from compression and acceleration in the accretion flow during black hole formation.

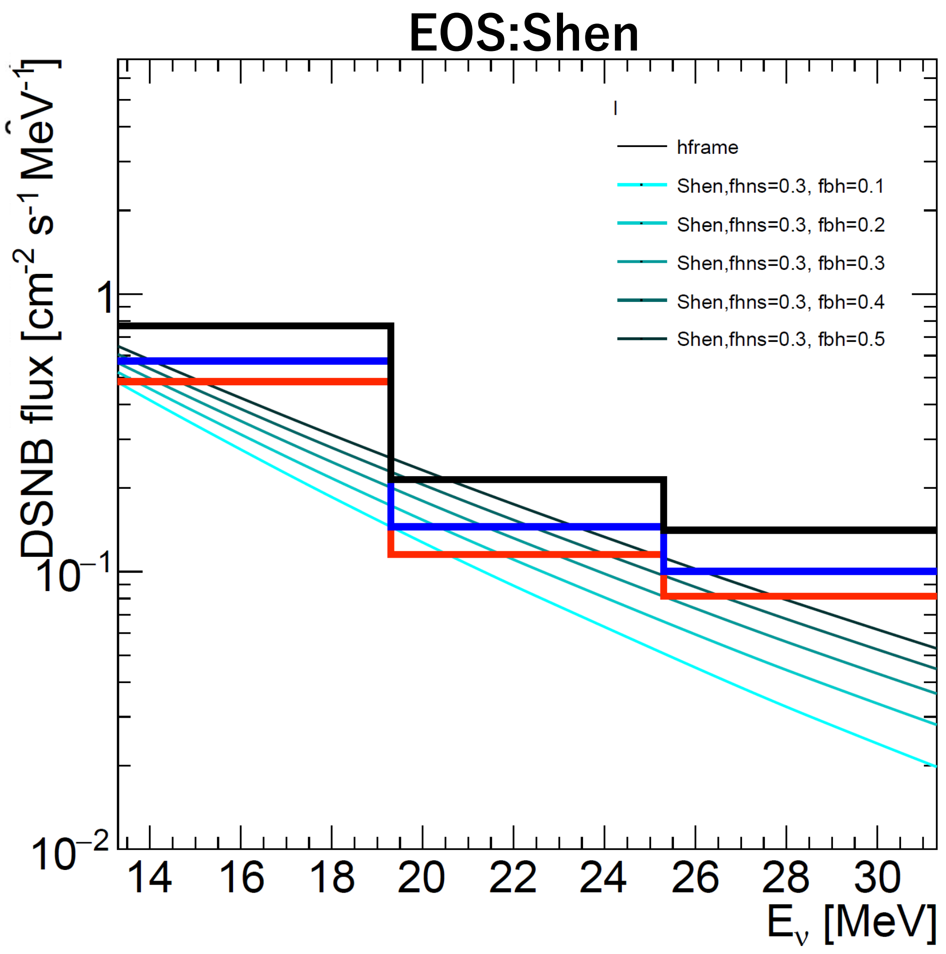
If the focus is on BH

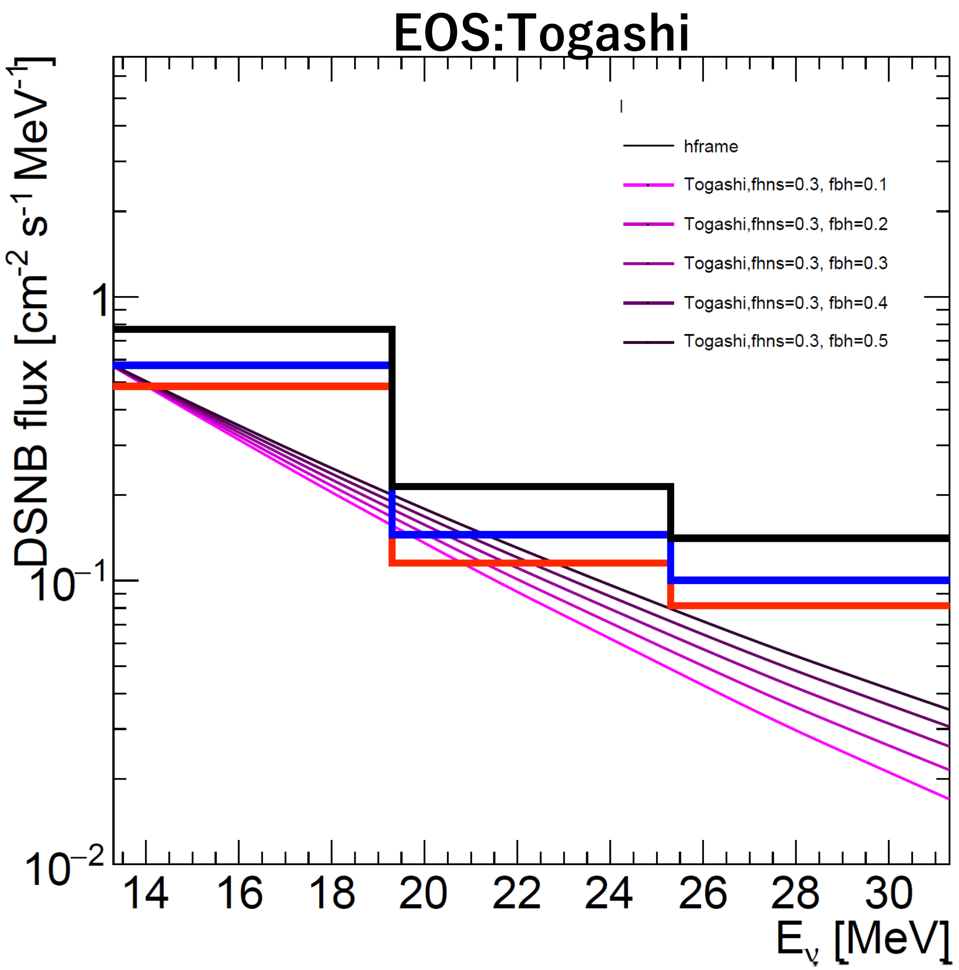
Ashida, Nakazato (2022)

3σ sensitivity M. Harada

- SK FY2028＋ 0 y
- SK FY2028＋ 5y(2033)
- SK FY2028＋10y(2038)

Is it possible to observe differences in the spectral slope above 20 MeV?





If the focus is on BH

Ashida, Nakazato (2022)

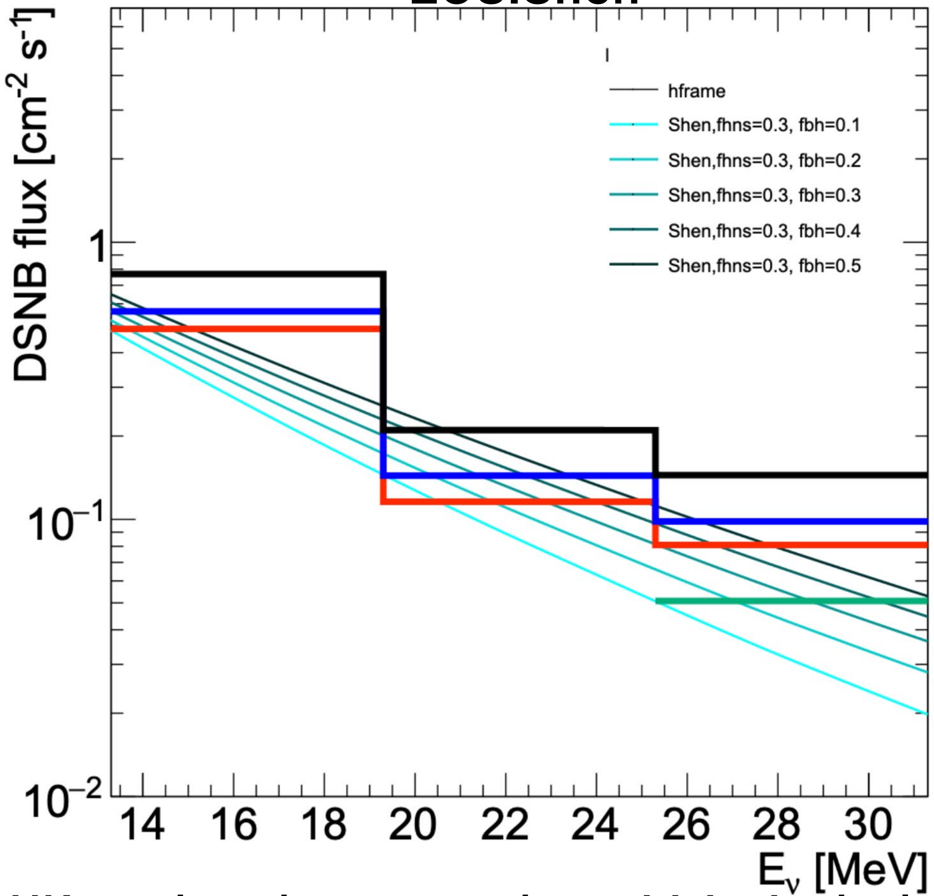
3σ sensitivity　Harada

- SK FY2028＋ 0 y
- SK FY2028＋ 5y(2033)
- SK FY2028＋10y(2038)
- HK FY2028+ 20y(2048)

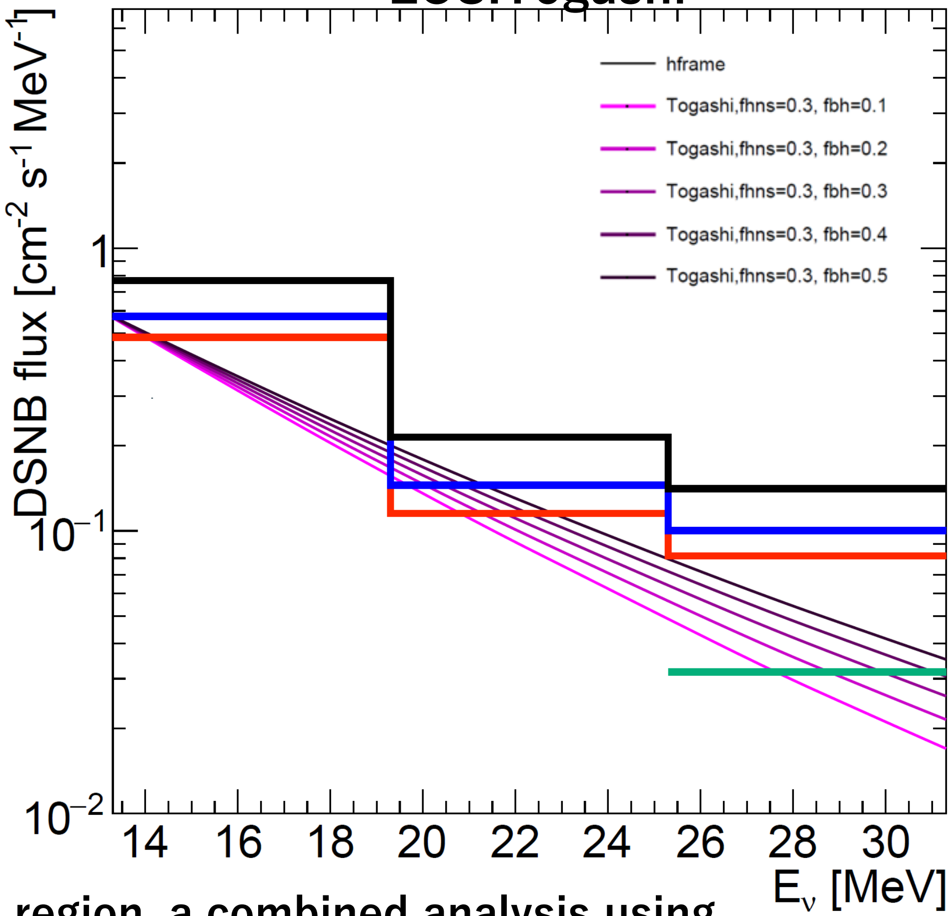
My proposal

Is it possible to observe differences in the spectral slope above 20 MeV?

EOS:Shen



EOS:Togashi



→ Until HK reaches the expected sensitivity in the low-energy region, a combined analysis using low-energy data from SK and high-energy data from HK will be important

Summary – The SK-Gd Journey beyond DSNB Detection

- After a long journey, we have conducted a DSNB search using 956.2 days of SK-Gd data.
  - The spectrum-independent analysis sets the most stringent limit to date on the astrophysical $\bar{\nu}_e$ flux.
  - By incorporating 5823 days of pure-water data, spectral fitting excludes the null-DSNB hypothesis at 2.3 σ for the Horiuchi+09 model (6 MeV, maximum).
- Our journey continues. With ongoing SK observations, we expect to reach a sensitivity of $<1\ \mathrm{cm^{-2}\ s^{-1}}$ above 17.3 MeV by 2029, bringing us closer to a potential discovery.
  - Further lowering the analysis threshold in SK-Gd will help us constrain the star formation rate (SFR) and the initial mass function (IMF).
- SK is now well-prepared not only for the potential discovery of the DSNB, but also for a decade-long observation program to rigorously test theoretical models.
  - We hope to continue observations through to Mark's 70th birthday—keeping SK active and impactful.