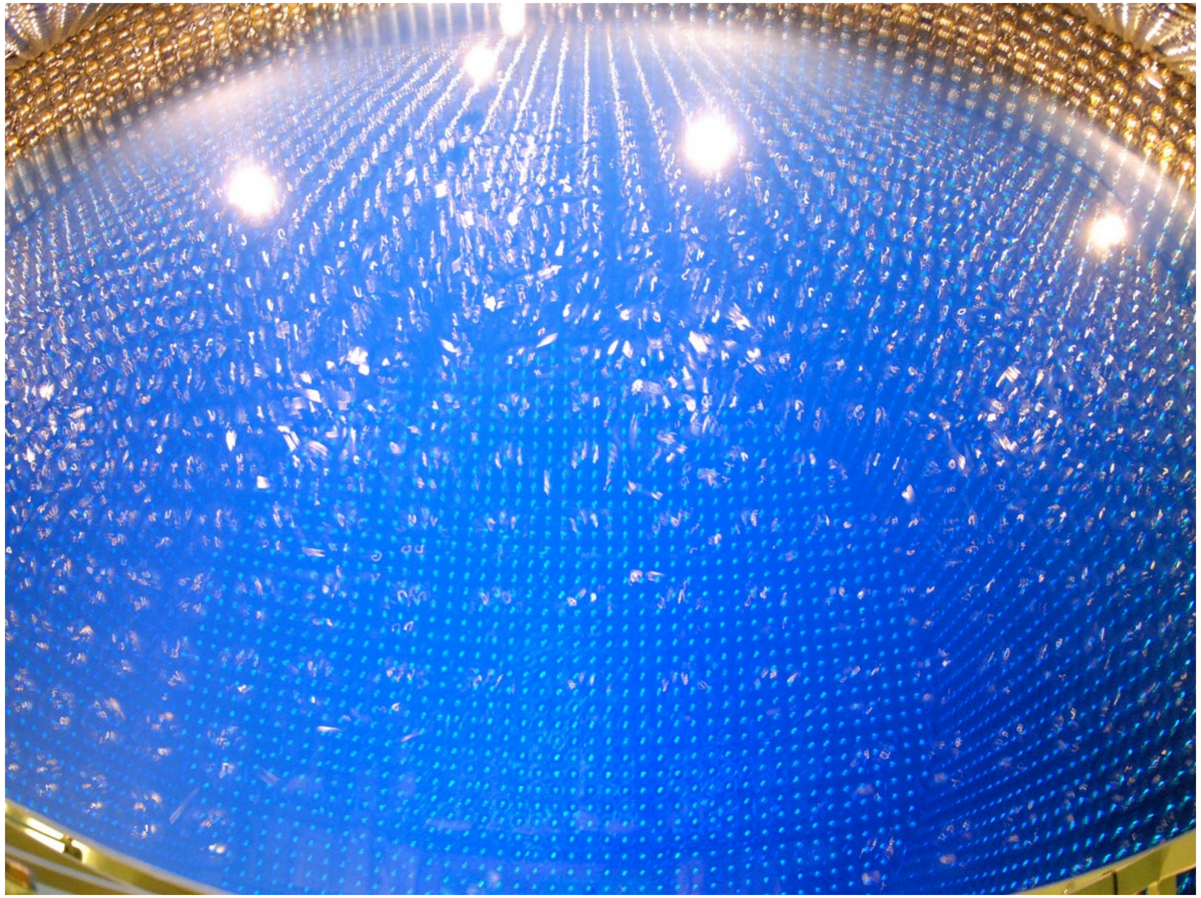
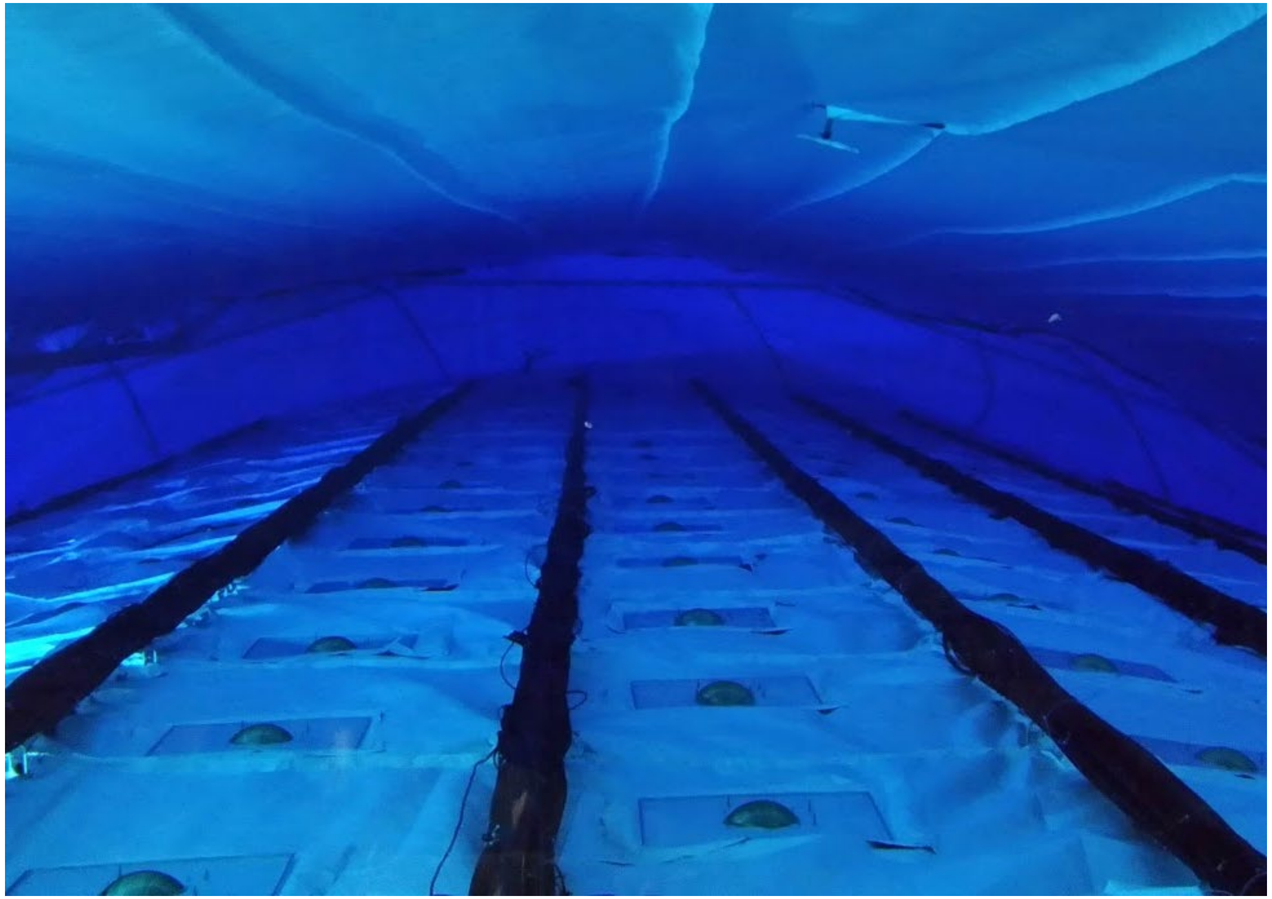




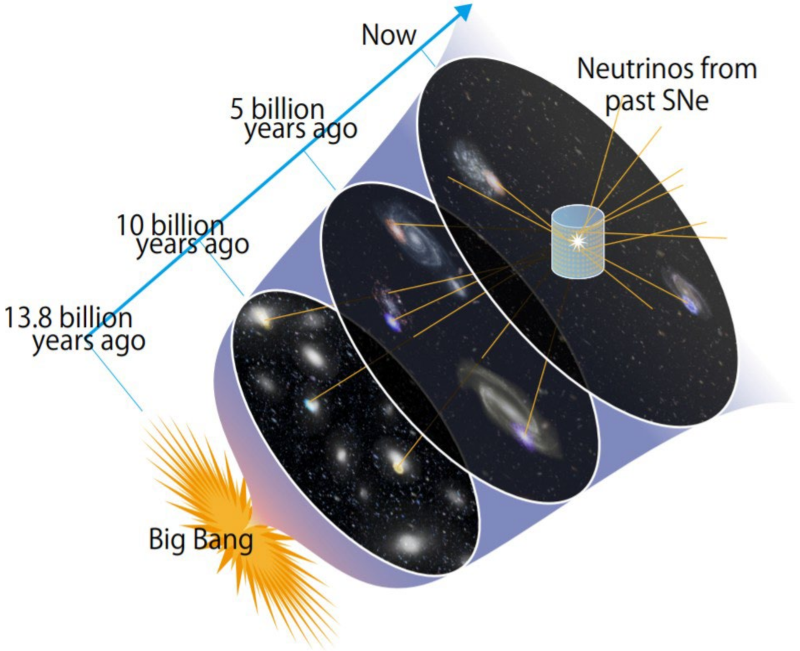
The Super-Kamioaknde Gadolinium Project

1st Yemilab Workshop 18 Oct 2022.
Hiroyuki Sekiya
Kamioka Observatory, ICRR, The University of Tokyo

KAMIOKA OBSERVATORY

Contents

- **Super-Kamiokande Gadolinium project**
  - Supernova and Diffuse Supernova Neutrino Background(DSNB)
  - DSNB search in SK-IV(pure water phase)
  - The Gd-loadings to Super-Kamioknade
  - Prospects for DSNB search



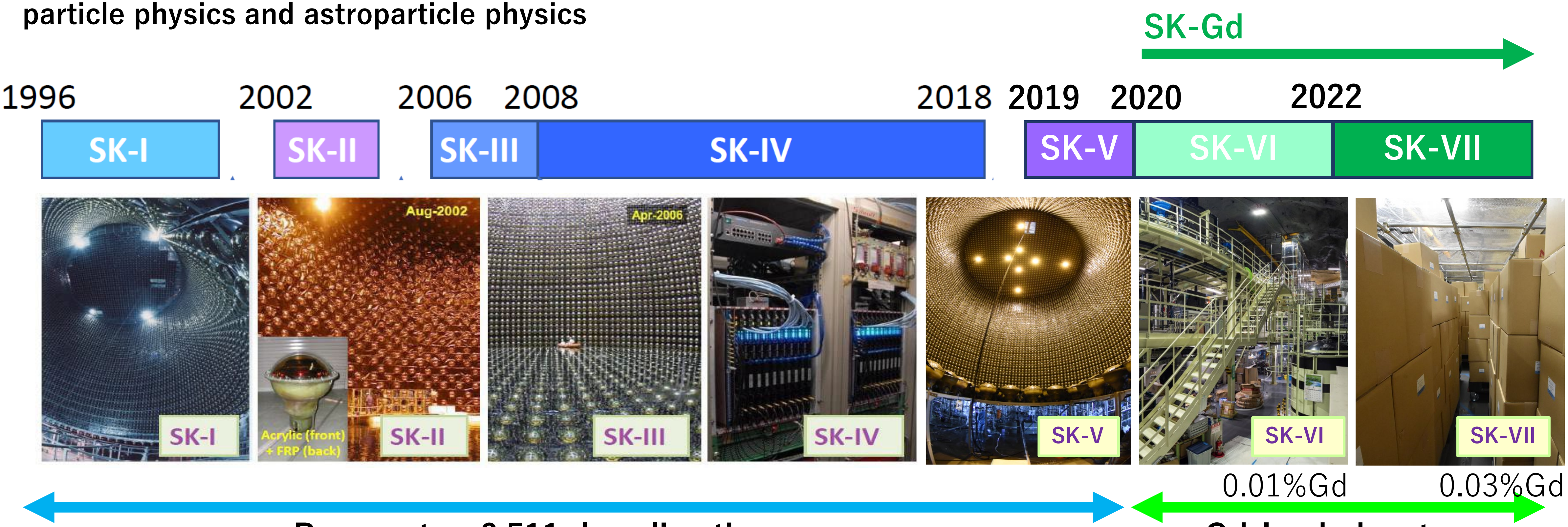
The Super-Kamiokande Collaboration

~230 collaborators
from 51 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
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
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
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

Super-Kamiokande experimental phases

For more than 25 years, SK has continued to provide a variety of topics in particle physics and astroparticle physics



Pure water 6,511 days live time

Gd-laoded water
583.3 days + the future…

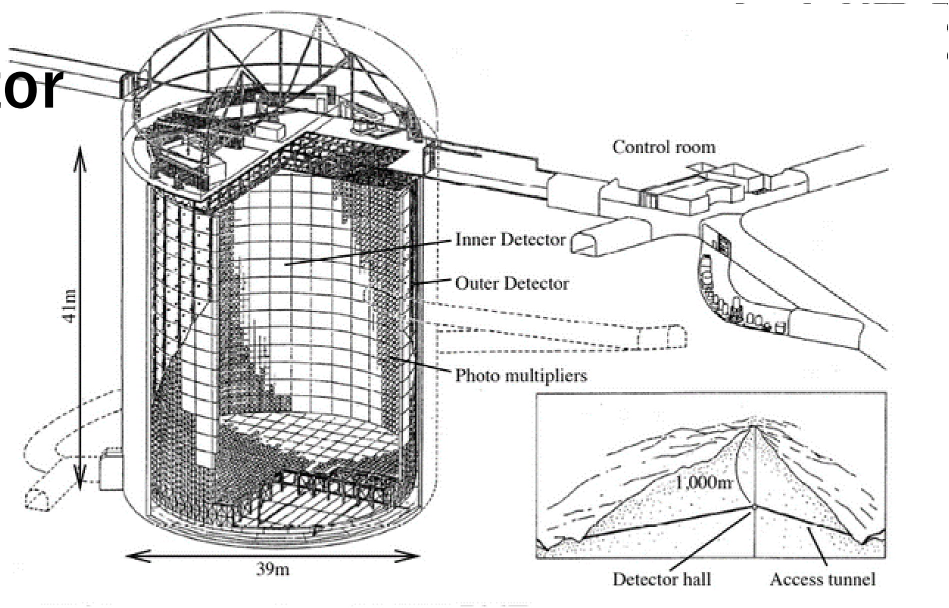
Gd in the Super-Kamiokande enables the detector to identify low-energy antineutrinos positively through the neutron capture.

The term “SK-Gd” is defined as after the start of the Gd-loading.

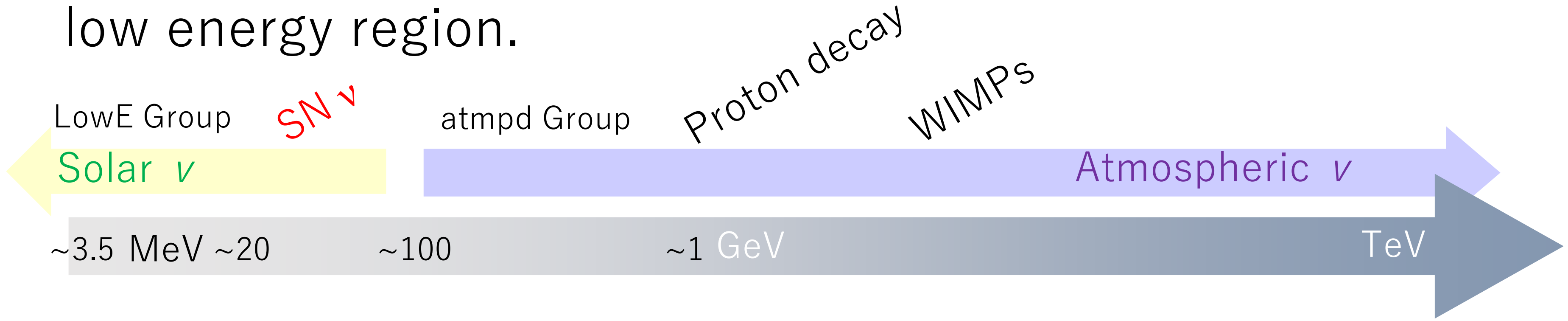
- **The phase of the experiment is still called SK-VI, SK-VII,...**

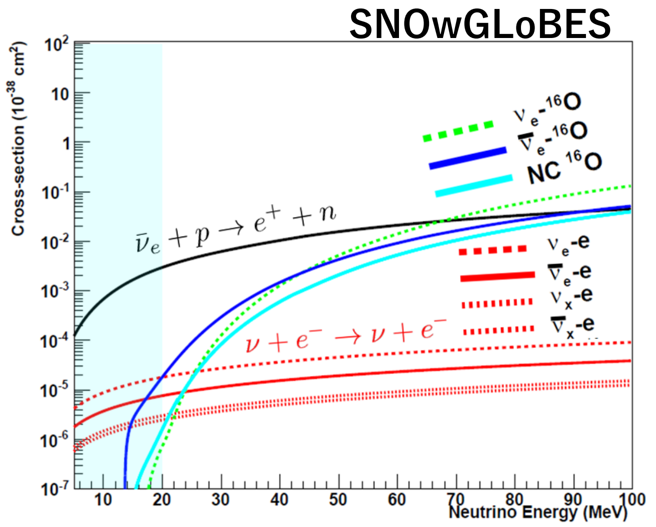
Super-Kamiokande VII (since July 5, 2022)

- **Ring imaging Gd-doped water Cherenkov detector**
  - **49.5k m^3 of pure water with 16.2 tons of Gd(0.03 w%)**
    - **39 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$**
    - **~75% Neutron capture efficiency**
  - **Target volume 32k m^3 for SN ν**
  - 11129 50cm PMTs for Inner detector
  - 1885 20cm PMTs for outer detector



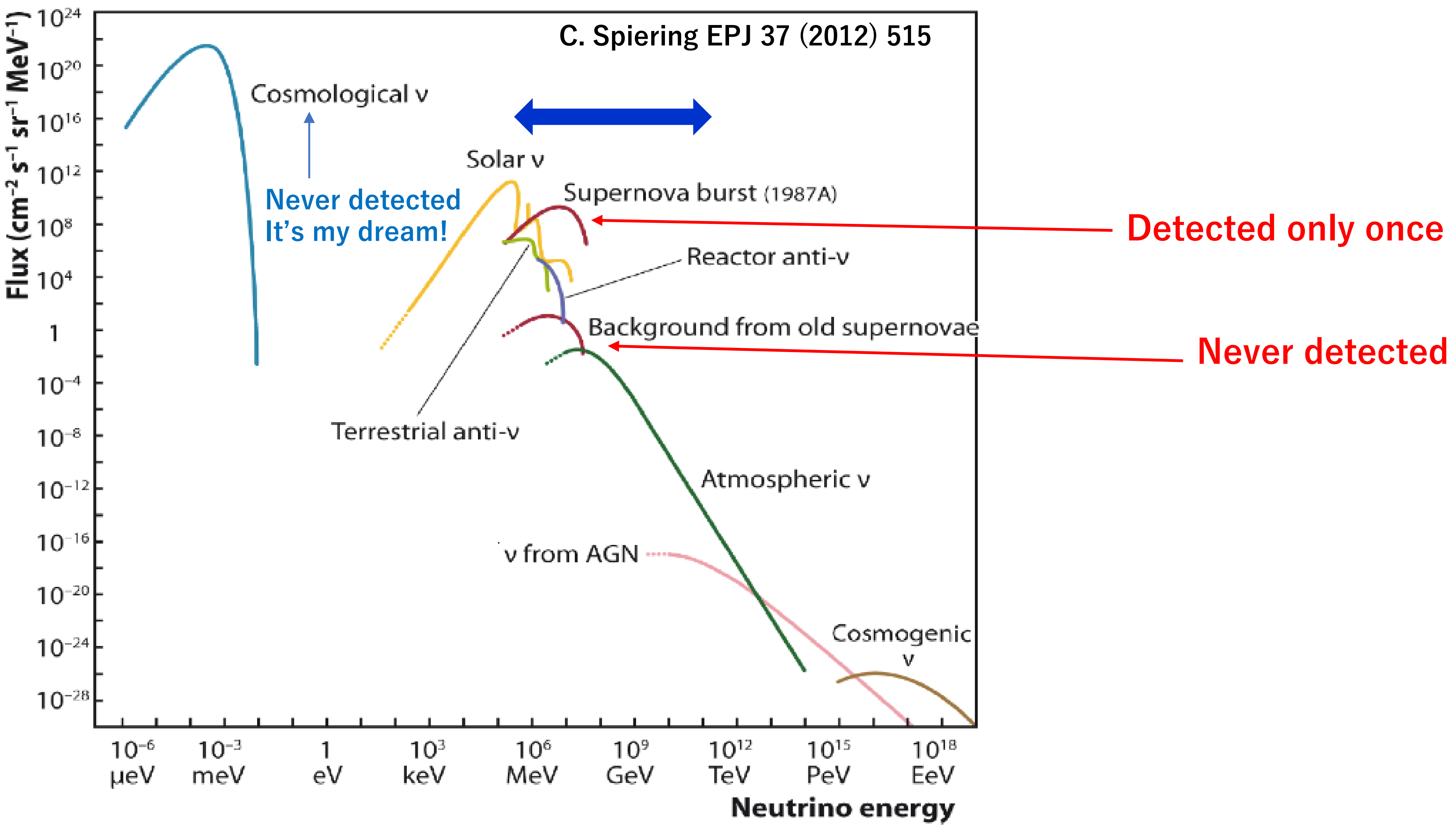
- 1km (2700 mwe) underground in Kamioka
- Measurable： Energy, neutrino types, and direction
- Most sensitive to $\bar{\nu}_e$ through inverse beta decay in the low energy region.





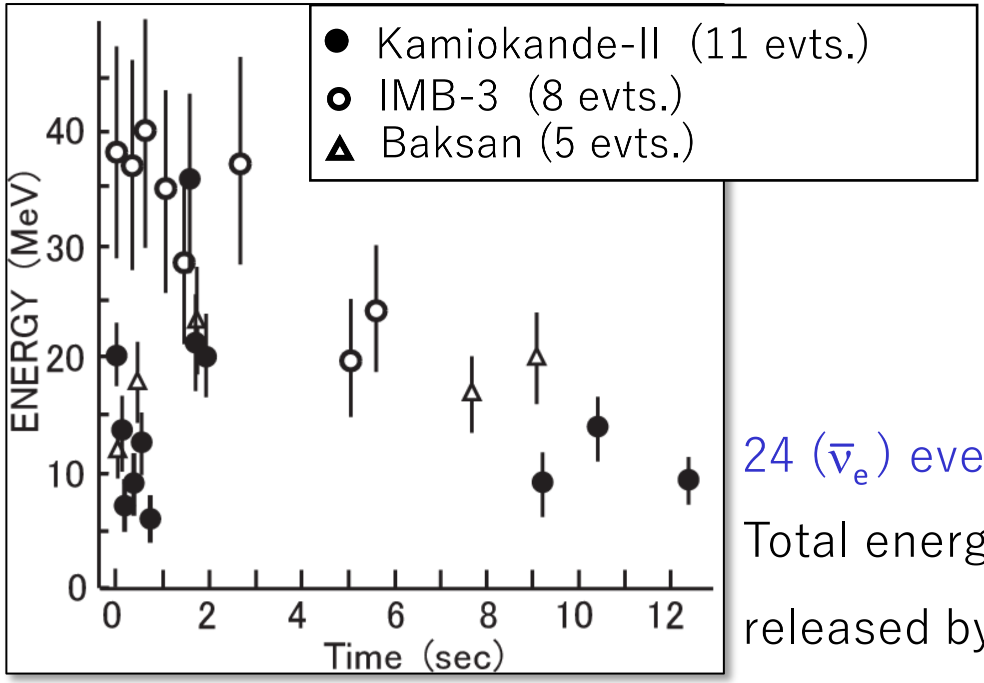
Targets of SK-Gd

There are two undetected neutrinos and one “detected-only-once” neutrino



Supernova neutrinos

- The only detected SN neutrinos are from LMC(50kpc) in 1987.

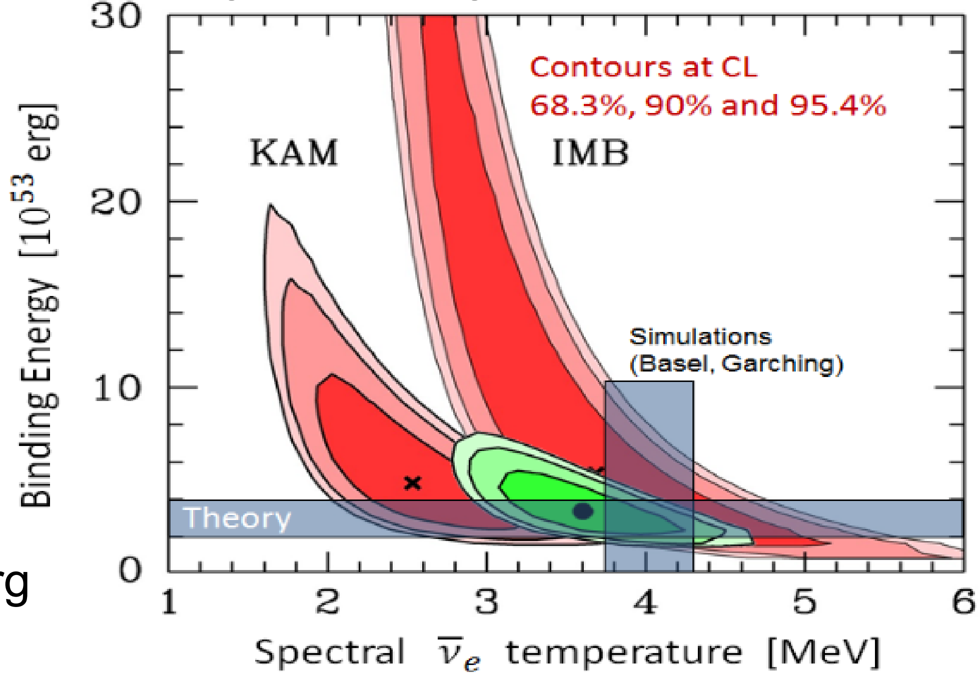


24 ($\bar{\nu}_e$) events in total.

Total energy

released by $\bar{\nu}_e$: ~5x10^{52} erg

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194



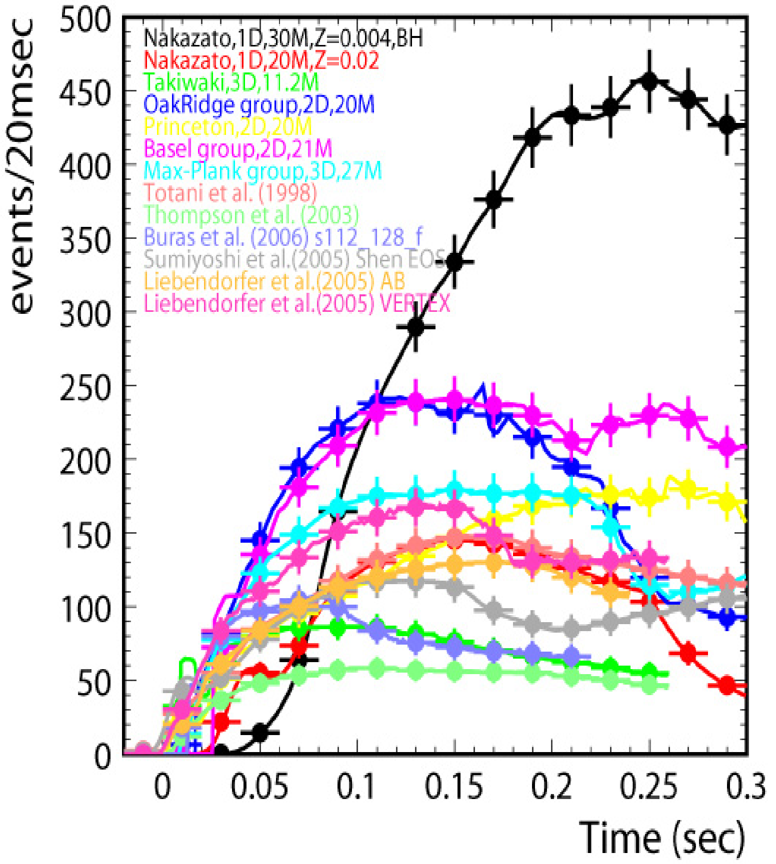
- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.

If SN happens in our Galaxy

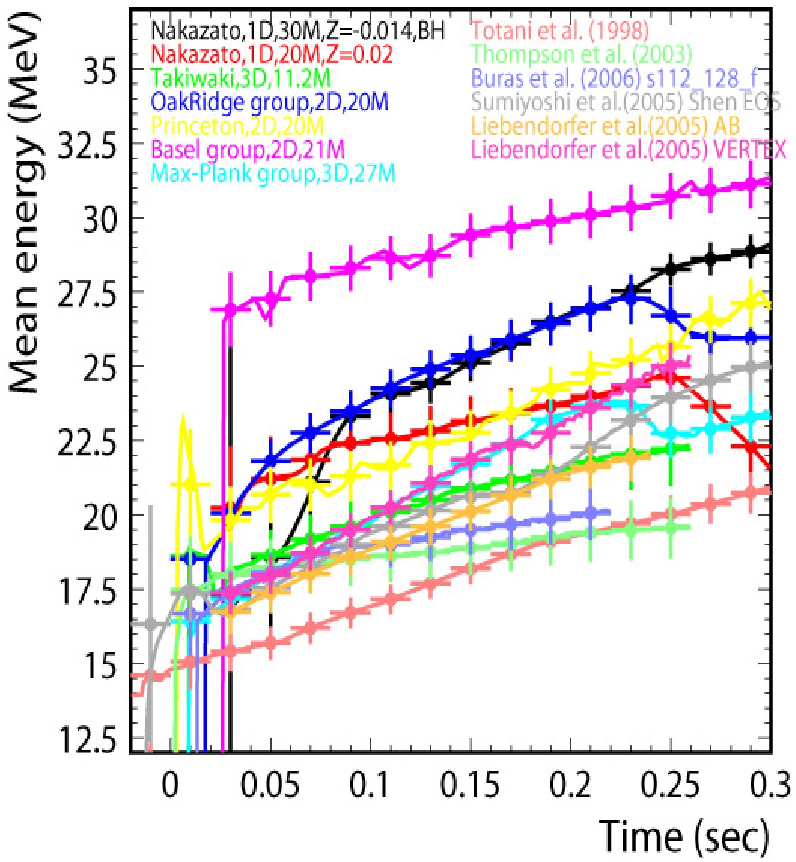
- SK should get enough statistics to discriminate models!

For SN at 10 kpc

Time variation of event rate



Time variation of mean energy



Total expected events in SK

	Totani 1998	Nakazato 20Msun, z=0.02
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

Can't wait!
Let's take another approach!

Diffuse Supernova Neutrino Background

Supernova Relic Neutrino

Not discovered but promising extra-galactic ν

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

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

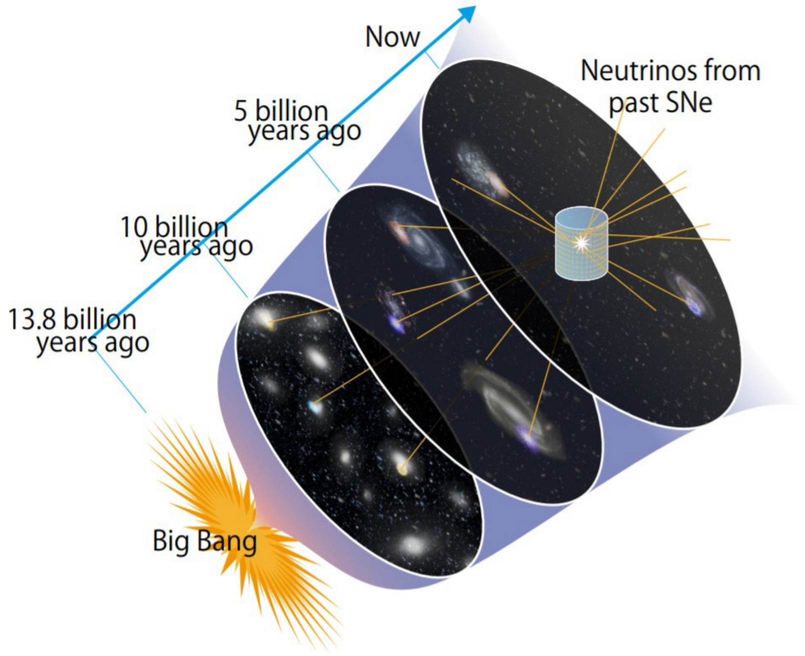
$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SN rate at z

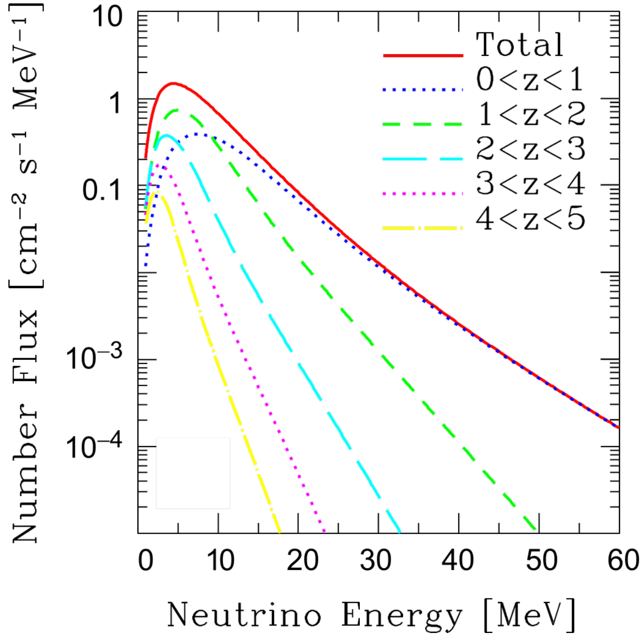
(averaged) SN spectrum

Access to

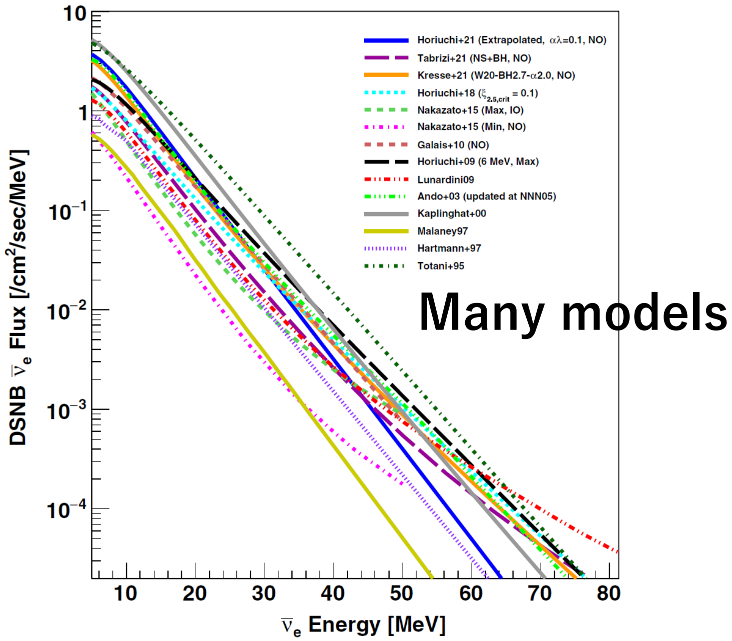
- ✓ **History of Star Formation**
- ✓ **BH formation**
- ✓ **Mechanism of the supernova explosion**



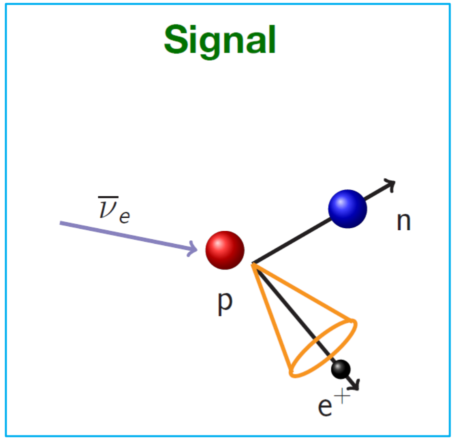
S. Ando 2004 *ApJ* **607** 20



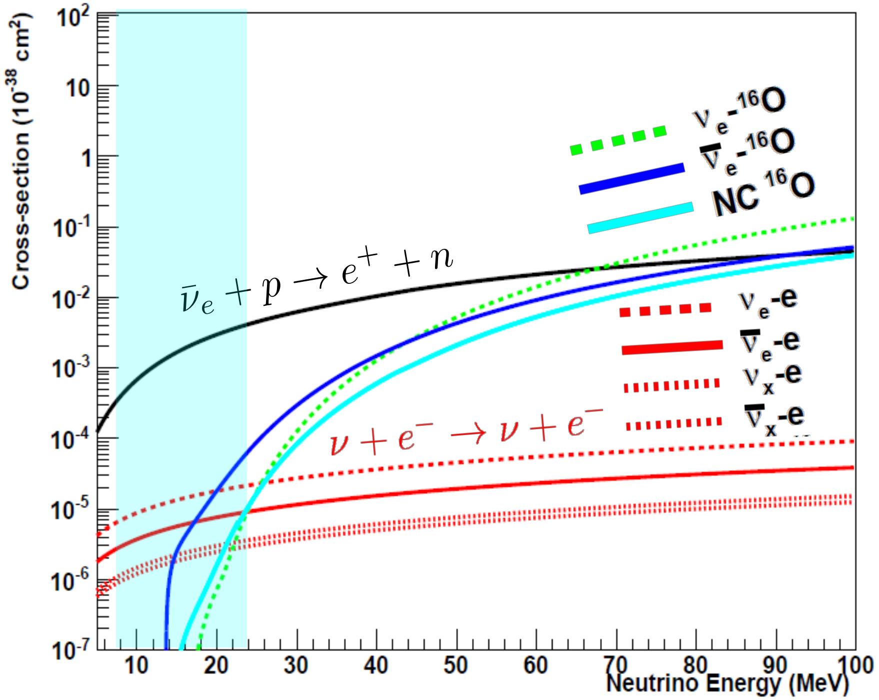
PRD **104**, 122002 (2021)

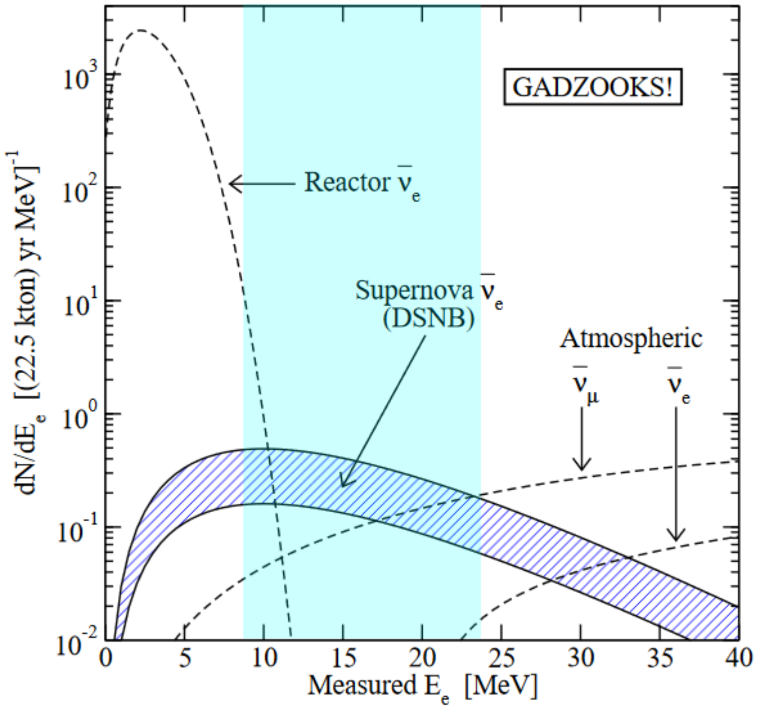


DSNB signal in Super-Kamiokande

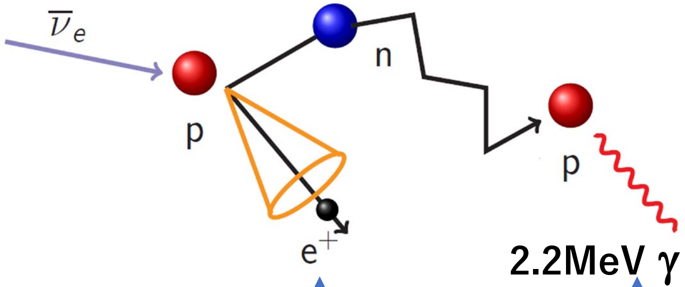


- **Main channel:** Inverse beta decay ($\overline{\nu}_e + p \rightarrow e^+ + n$).
- **Signal window:** Between reactor neutrinos and atmospheric neutrinos.
- **Event rate:** A few interactions/year/SK





Neutron-tagging is the key!
In pure water



Delayed coincidence
…Low efficiency

The spallation background

Spallation products of oxygen nuclei induced by the ~2Hz muons

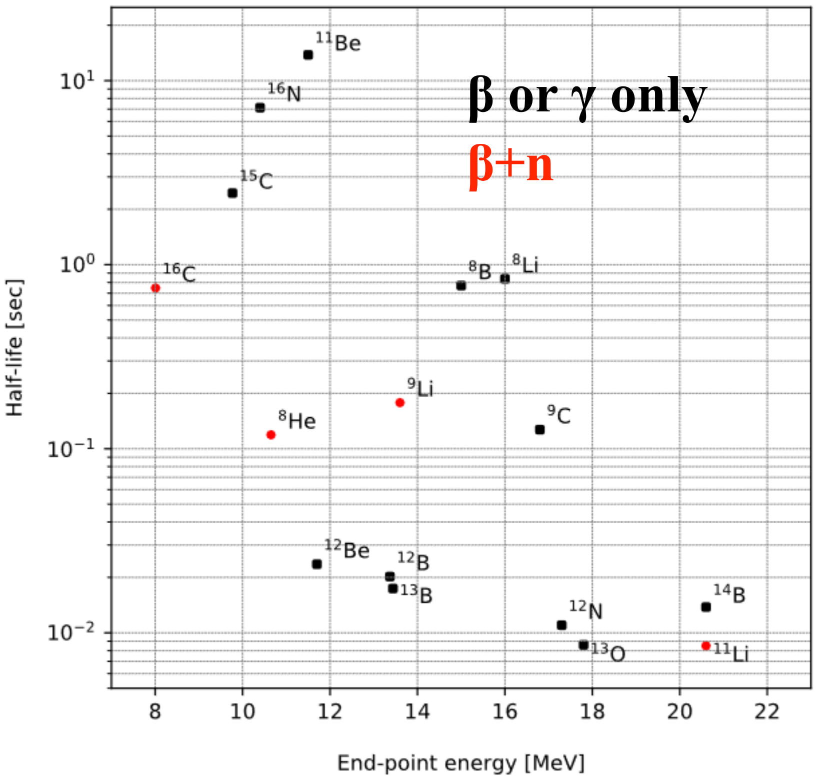
- Below 20 MeV, the associated background is 10^6 times higher than the DSNB flux prediction.

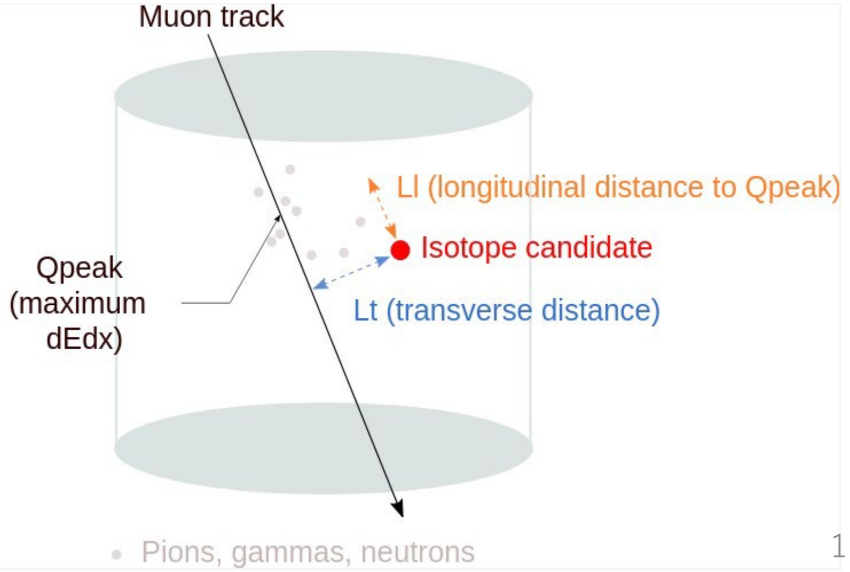
BG reduction is essential

- Nuclei that decay without neutrons(>99%)
  - Correlation with muons and **the neutron tagging**
- Nuclei that decay with neutrons (e.g., ^{9}Li, < 1%)
  - Correlation with muons is the only useful information

Cuts-based reduction uses distance and time difference from muons, etc.

- Removal efficiency: > 90%
- Signal efficiency: 50-90% (depending on energy)

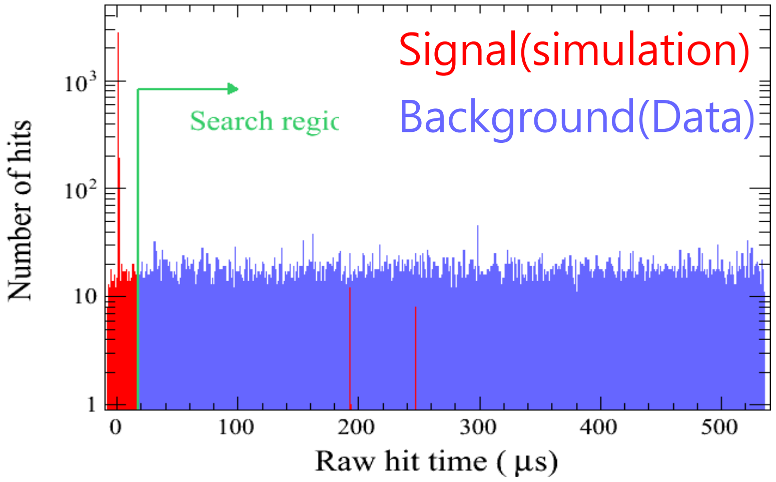


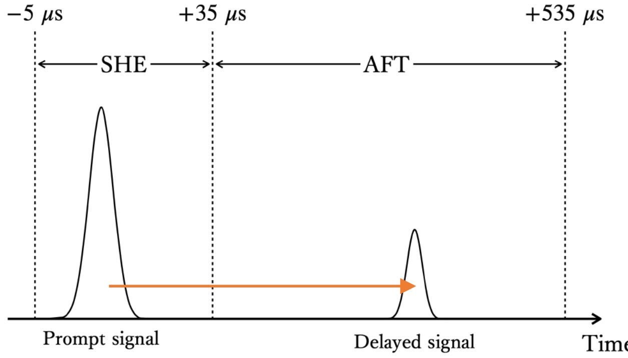


Neutron-tagging in pure water

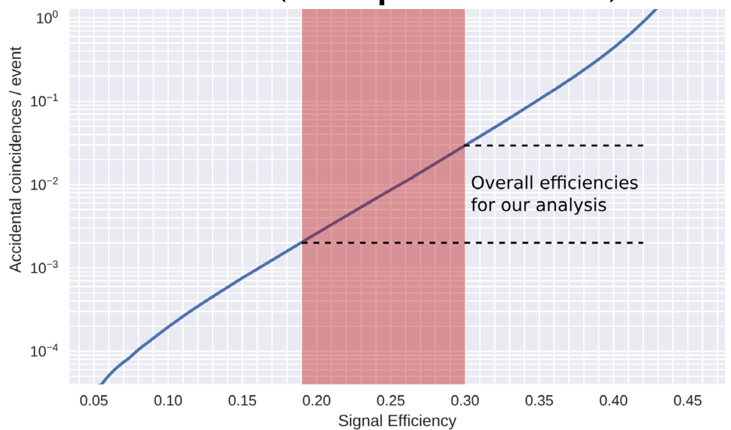
$n + H \rightarrow D + \gamma\,(2.2\ \mathrm{MeV})$

- **Neutron capture by H （τ ~200μsec)**
  - 2.2MeV →~7PMT hits (out of 11000PMTs)
  - Buried in the low energy background events (dark noise in PMT, RIs, radon, etc.)
- **Trigger scheme in DAQ**
  - If ~9 MeV or higher events exist (Super High Energy trigger), all hits for the next 500 μs are recorded (AFTer trigger).
- **Machine learning-based neutron selection algorithm**
  - 22 parameters used in BDT.
    - PMT hit pattern, cluster hits, the distance between the primary and delayed events, etc.
  - Trained for 2.8×10^8 neutron candidates.
    - With 2×10^6 simulated neutron captures and accidental coincidence events
  - Efficiency: 18~30% with 0.2~3% mis-tagging.
  - Systematic uncertainty: 12.5% checked by Am/Be calibration.





ROC (BDT performance)



The Results form SK-IV

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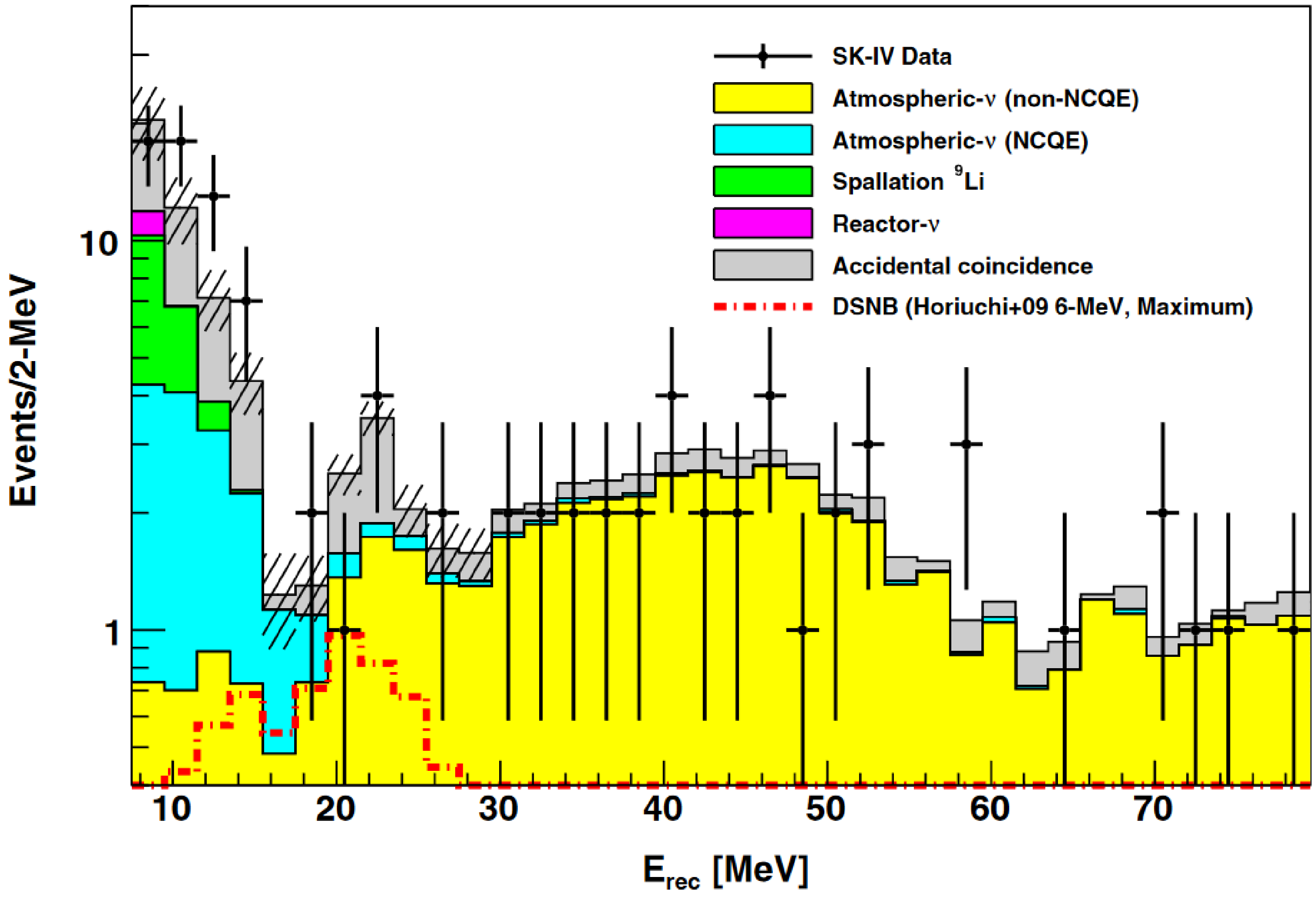
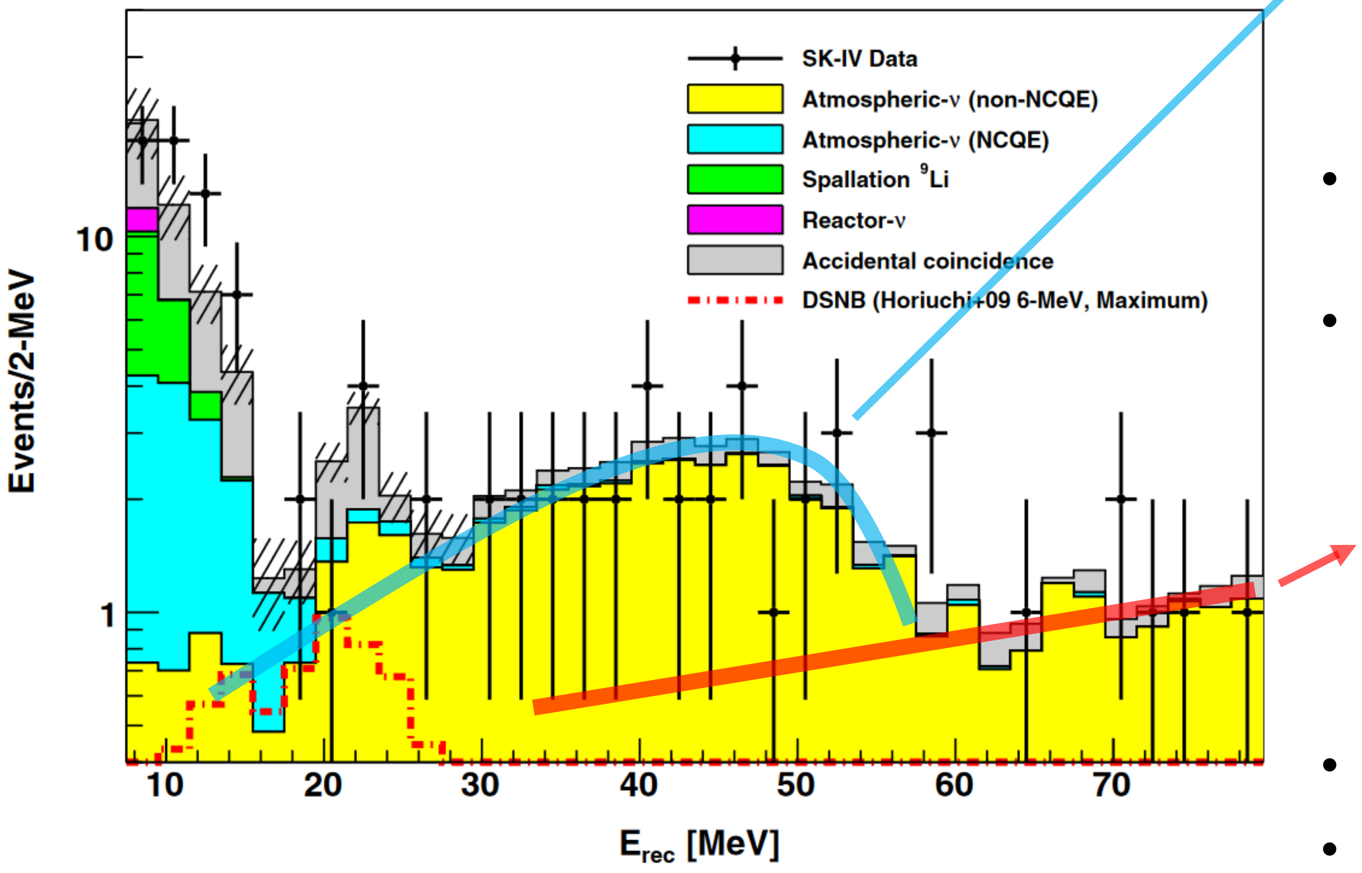
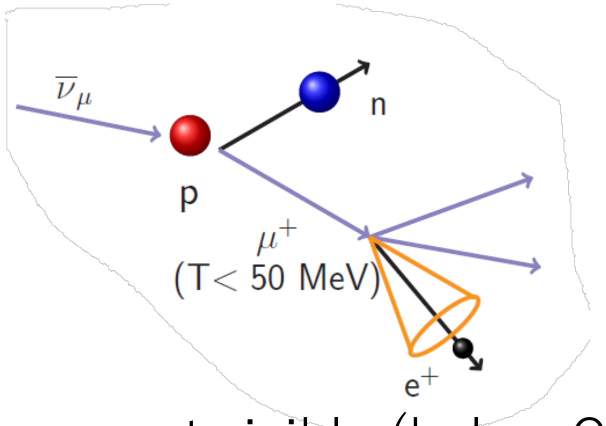


Background : Atmospheric ν CC

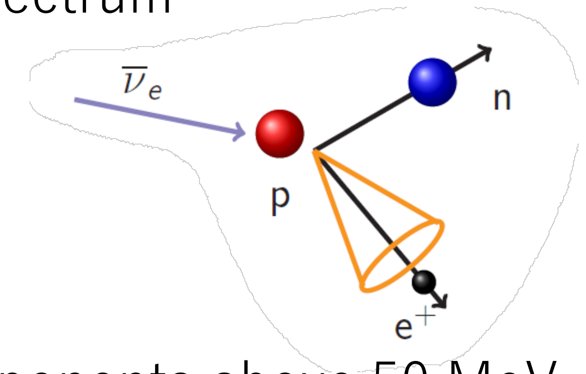


ν_μ CC



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

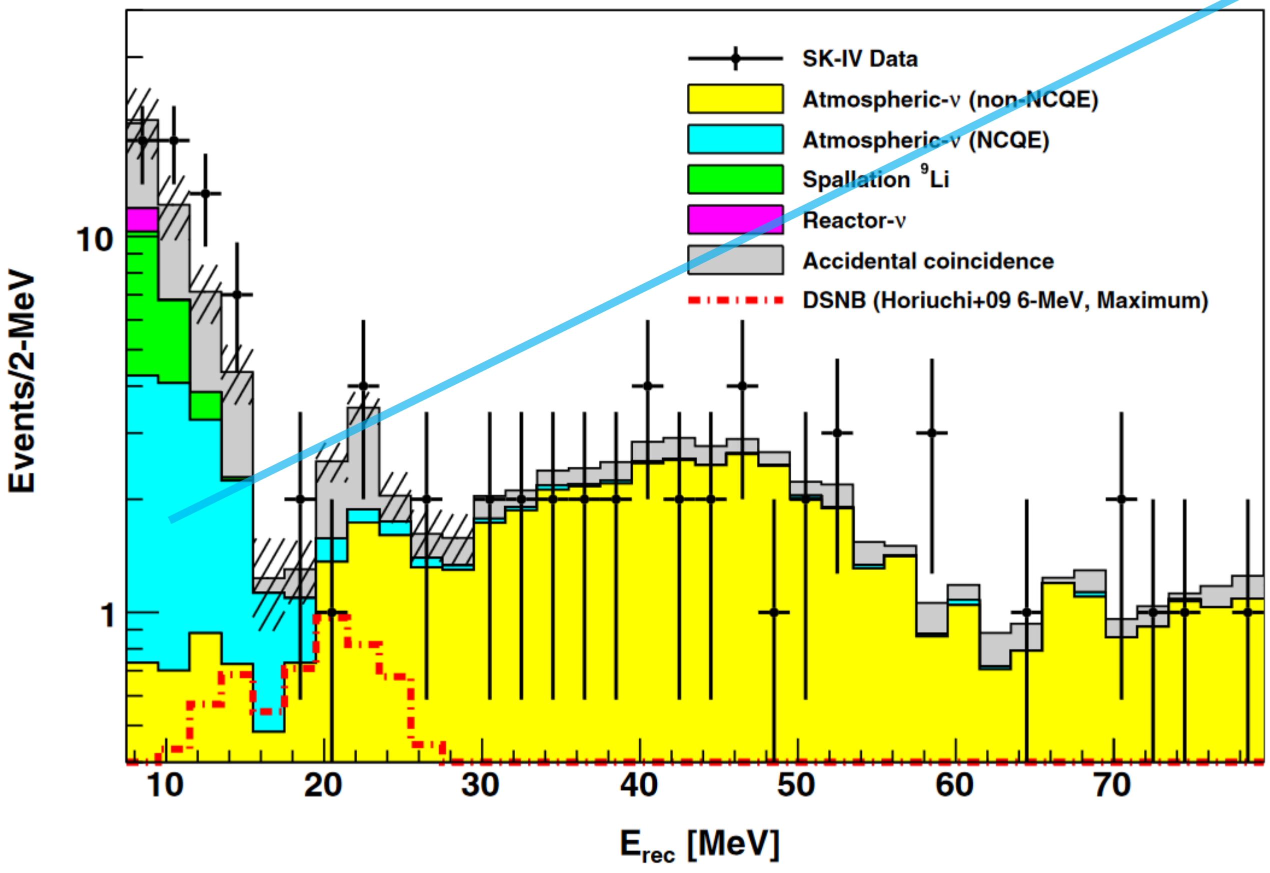
ν_e CC



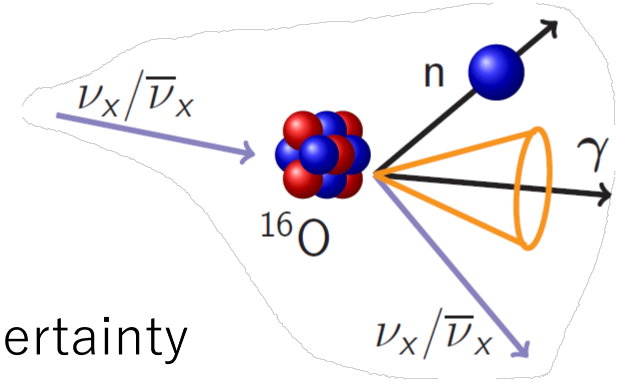
- Major components above 50 MeV
- Small contribution to DSNB region

- These BGs (using >30MeV region) are subtracted with 20% systematic uncertainty

Background : Atmospheric ν NC



NC(QE)



- Largest uncertainty

  Systematic error: 60-80% (energy-dependent)

Atm. ν flux

× NCQE cross-section

(←T2K measurement)

× Number of generated neutrons

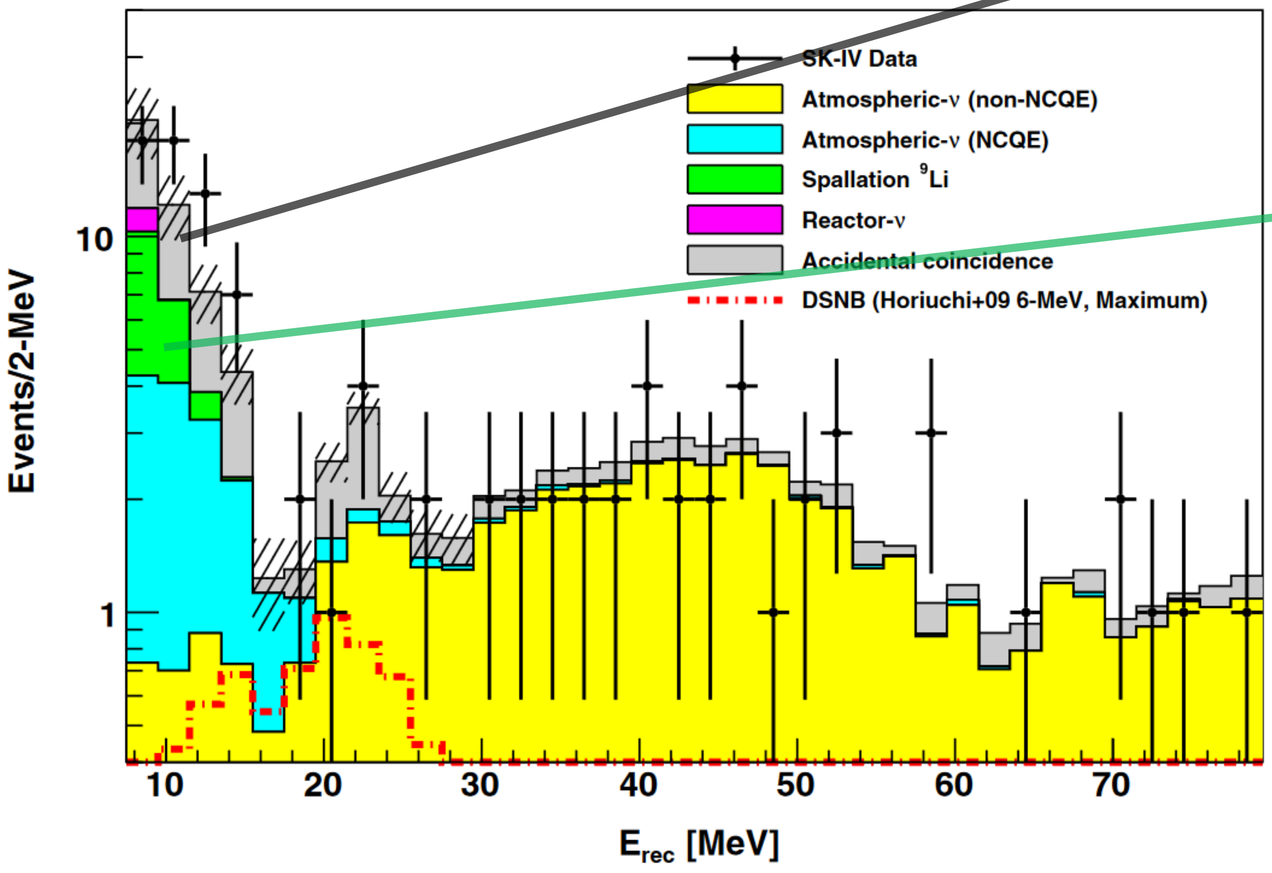
(←T2K CC measurement)

× Neutron detection efficiency

(←Am/Be calibration)

Understanding and reducing this uncertainty is essential!

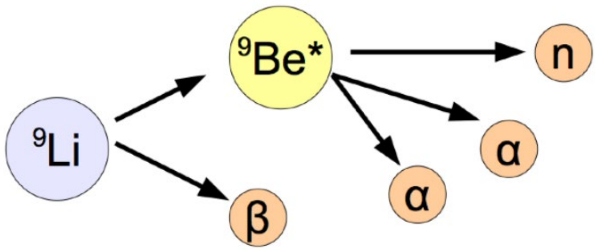
Background : Accidental and Spallation ^{9}Li



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

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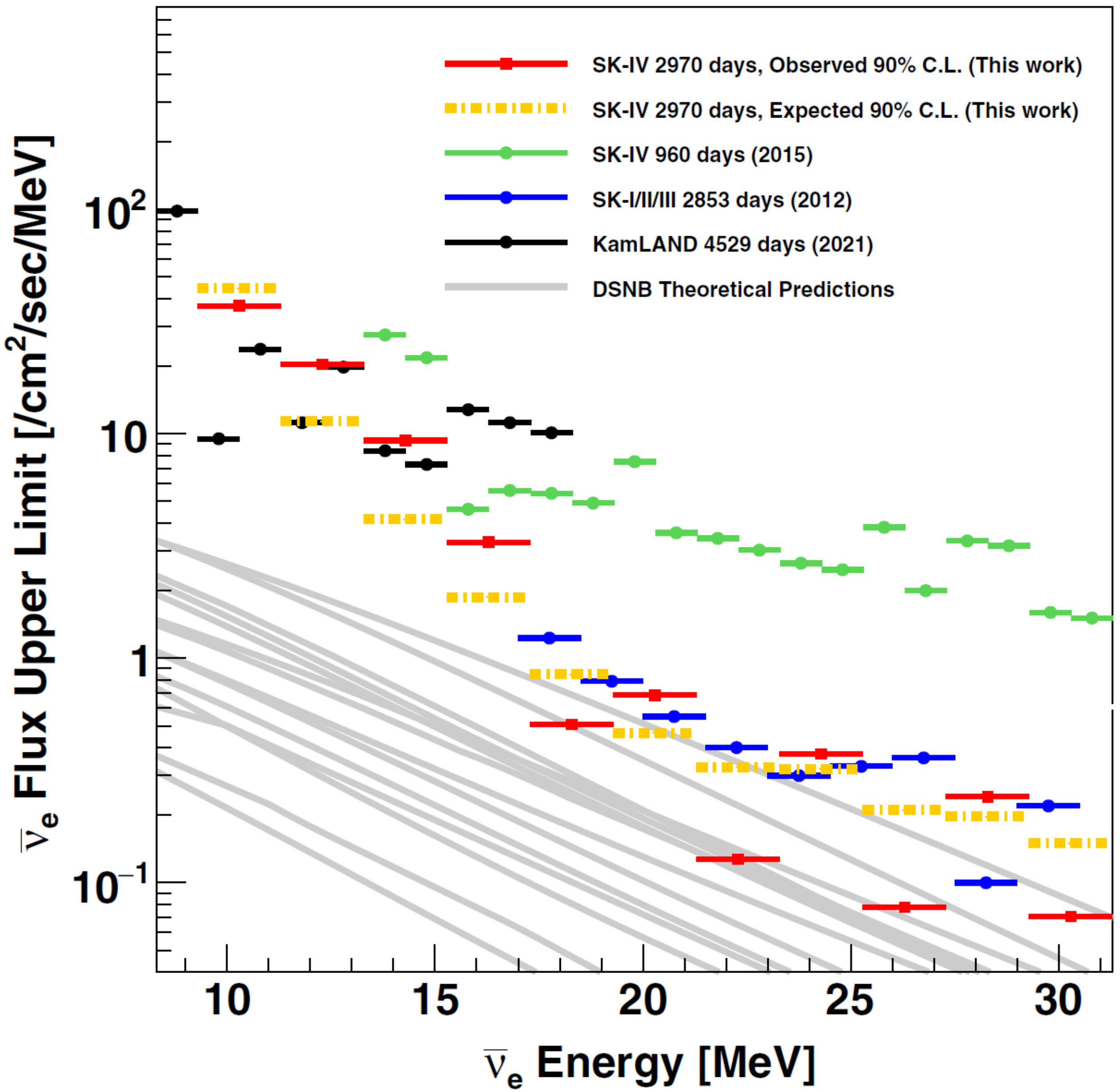
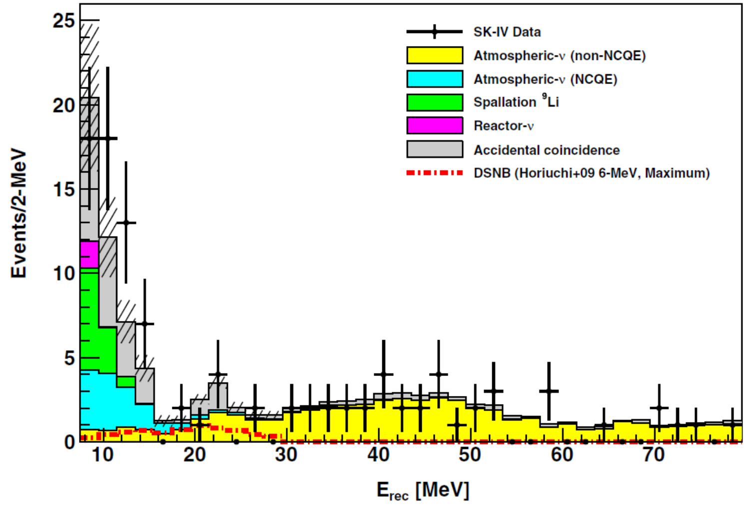
- Strongest limit above 15 MeV
- Already reached some model prediction regions



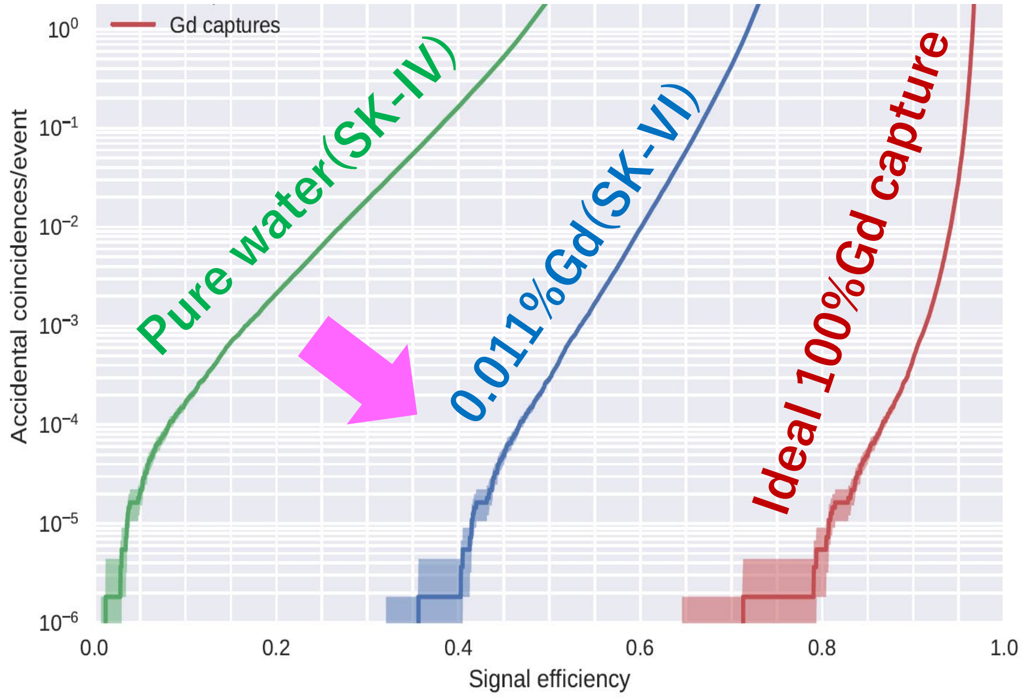
How Gd-loading helps?

In SK-IV(pure water), accidental coincidence remains due to low neutron tagging efficiency

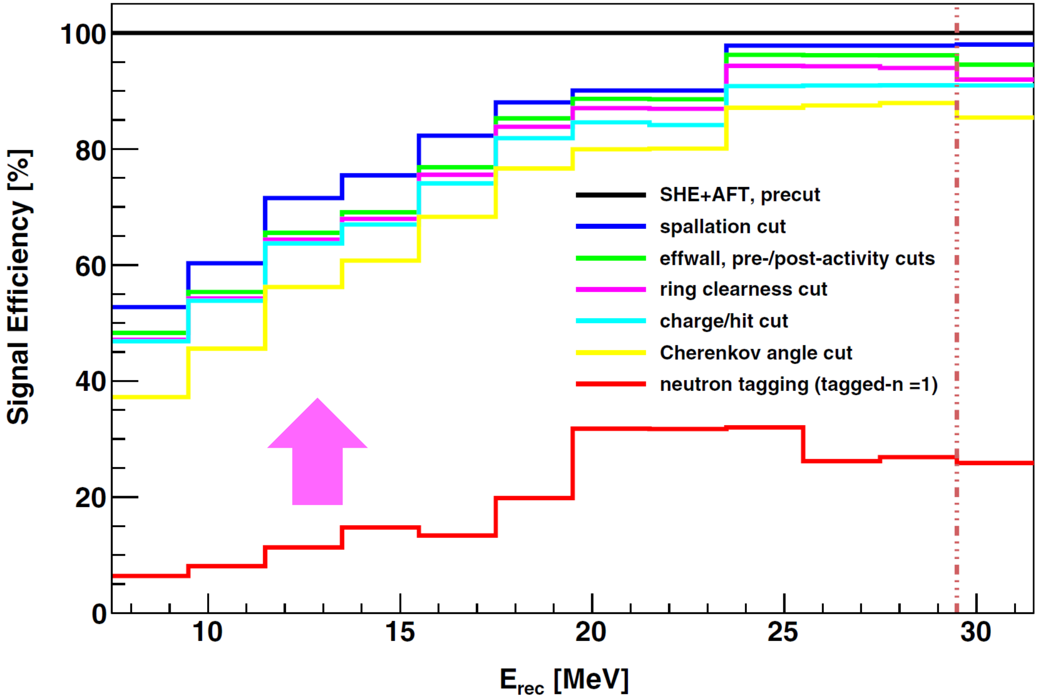


- Reduction of accidental BG (approx. 1/10) with high neutron detection efficiency.
- Also signal statistics increases (2~3 times)

ROC curve (n tagging BDT performance)

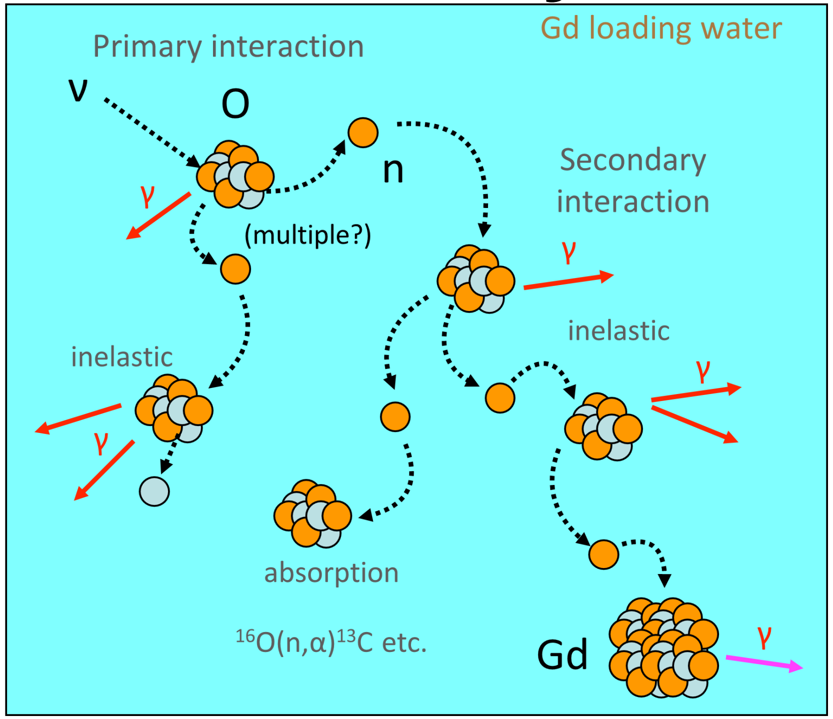


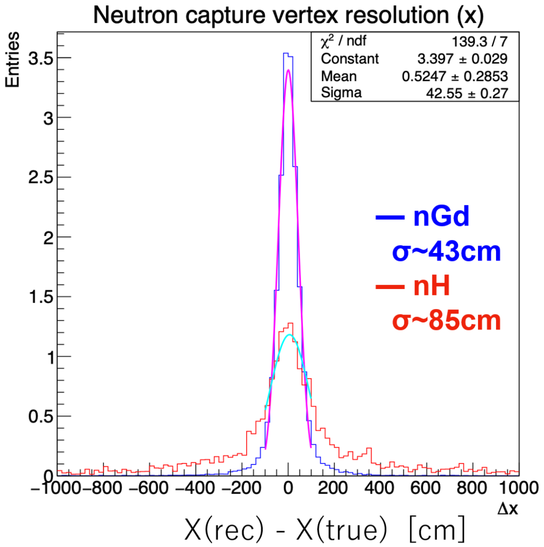
Pure water(SK-IV)

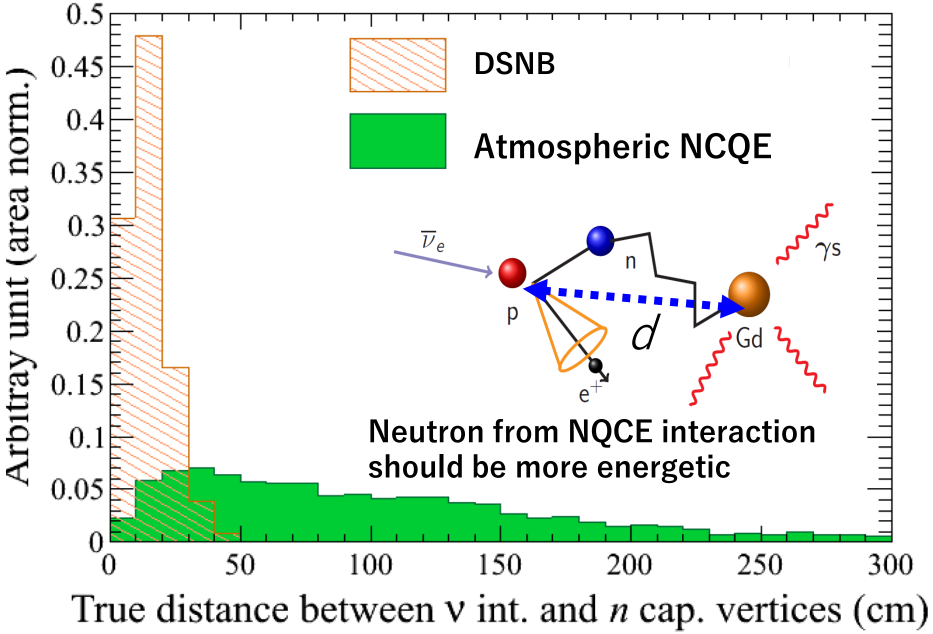


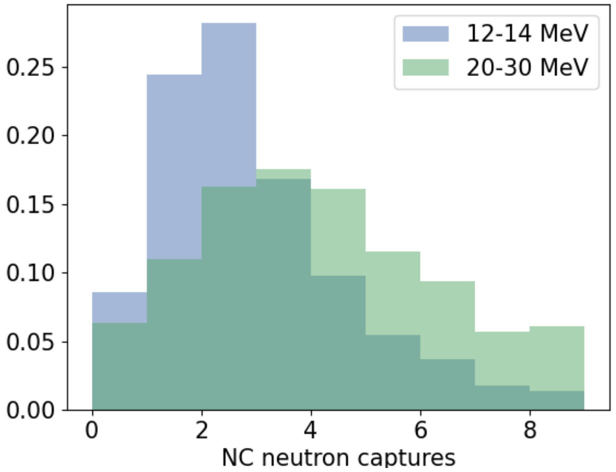
Further improvements expected (understudy)

- The next largest BG that should be reduced is the atmospheric NCQE.
- Gd also helps to reject the NCQE BG.
  - Neutron multiplicity counting
  - The neutron capture vertex resolution



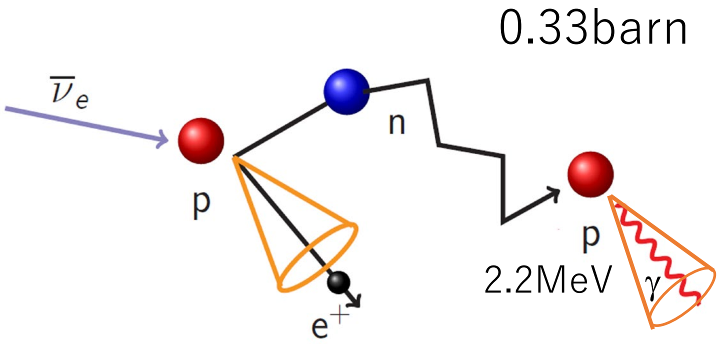


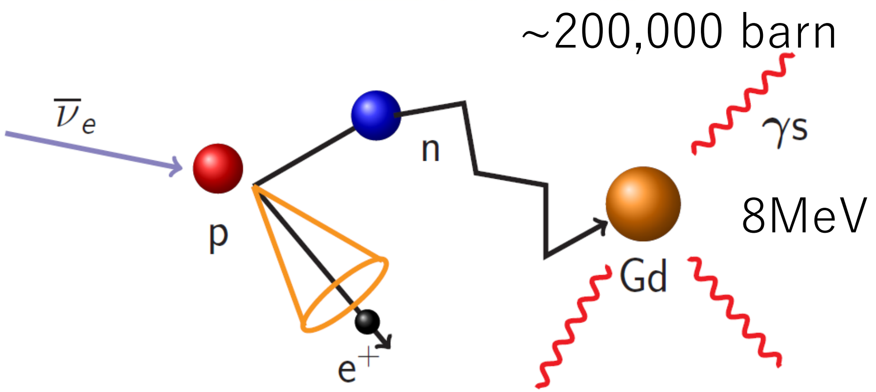


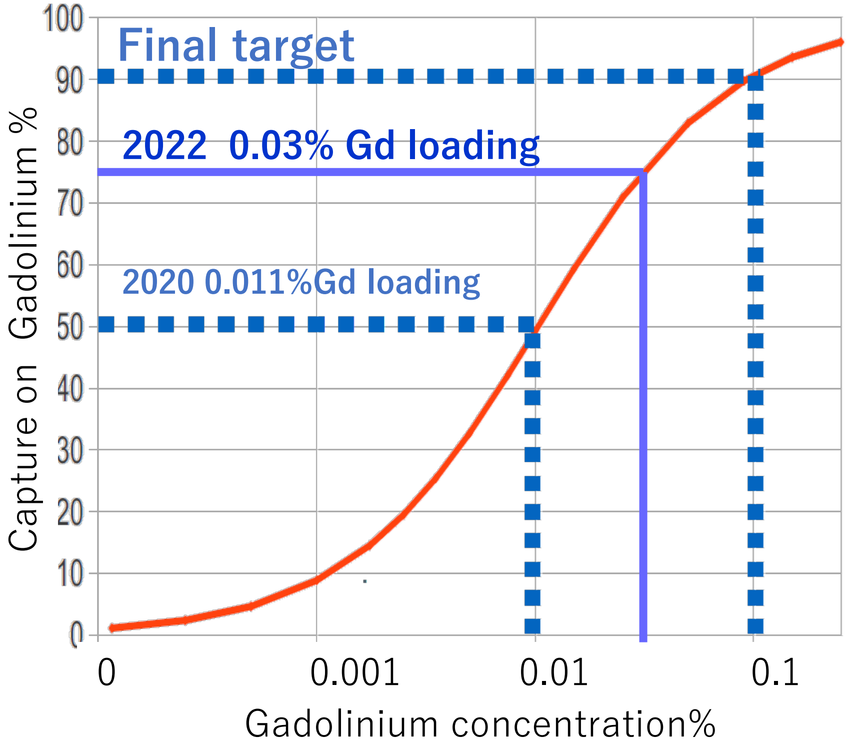


SK-Gd (2020-)

Isotope	Natural abundance ratio [%]	Thermal capture cross section [barn]
^{152}Gd	0.20	740
^{154}Gd	2.18	85.8
^{155}Gd	14.80	61100
^{156}Gd	20.47	1.81
^{157}Gd	15.65	254000
^{158}Gd	24.84	2.22
^{160}Gd	21.86	1.42
^{1}H	99.99	0.33
^{16}O	99.76	0.0002
^{32}S	94.85	0.53





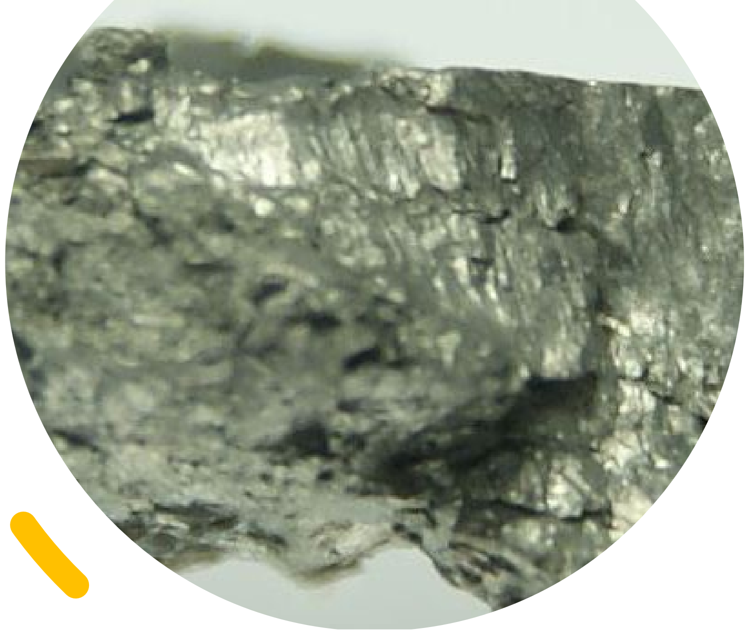


Gd-loading to SK

- Significantly enhances detection capability of neutrons from $\bar{\nu}$ interactions
- Initial loading was conducted in July-August 2020. 0.011% Gd concentration was achieved.
- The 2nd loading just finished on July 5, 2022. 75% of neutrons would be captured by Gd

Gd-loading is not trivial! It's Chemistry!

- Gd metal is not soluble in water. A compound must have been selected.
  - Gadolinium chloride solution rusts even SUS tanks
  - Cherenkov light does not pass-through gadolinium nitrate solution
- **Gadolinium sulfate octa-hydrate** $Gd_2(SO_4)_3 \cdot 8H_2O$ was chosen.



Other difficulties we have overcome

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

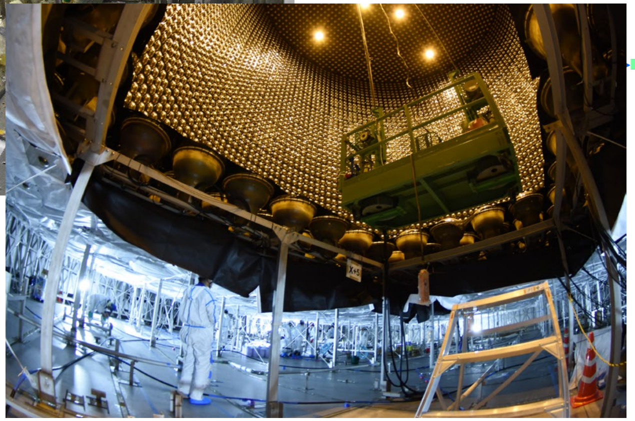
- **Stopping the SK leakage**
  - Estimation of the leak location
  - Development of the leak-fixing method
- **Reduction of RIs from $Gd_2(SO_4)_3$ powder**
  - Test of Ra removal resins
  - Material screening with HP-Ge detectors
  - High sensitivity measurement with ICP-MS
- Test with the EGADS demonstrator
  - 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

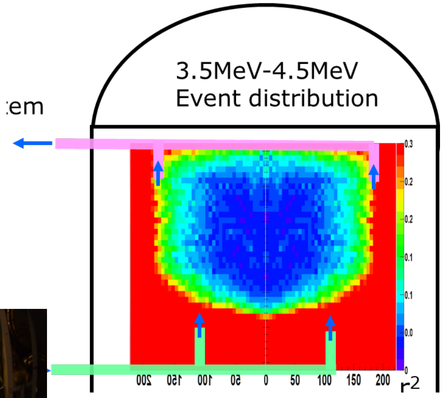
Stopping the SK leakage

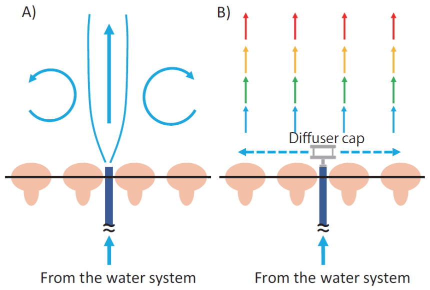
The tank was refurbished with water sealing by painting specially developed resin on all the welding lines from May 31, 2018, to January 29, 2019.

Piping upgrade and water outlets modification

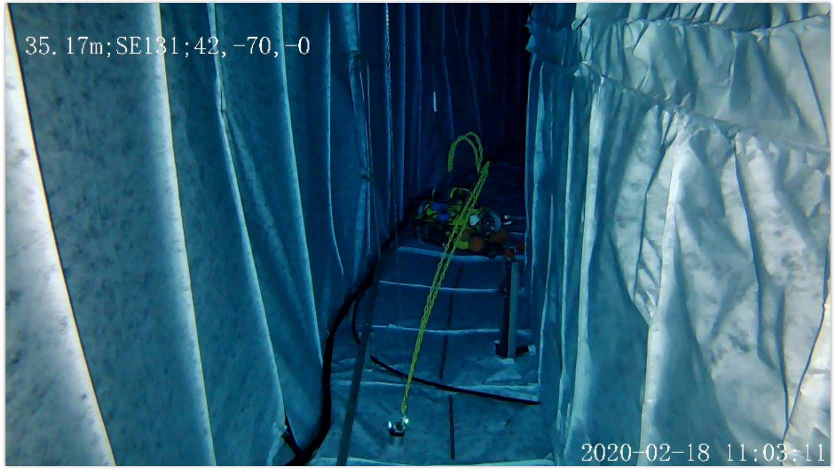
For doubling the circulation flow rate







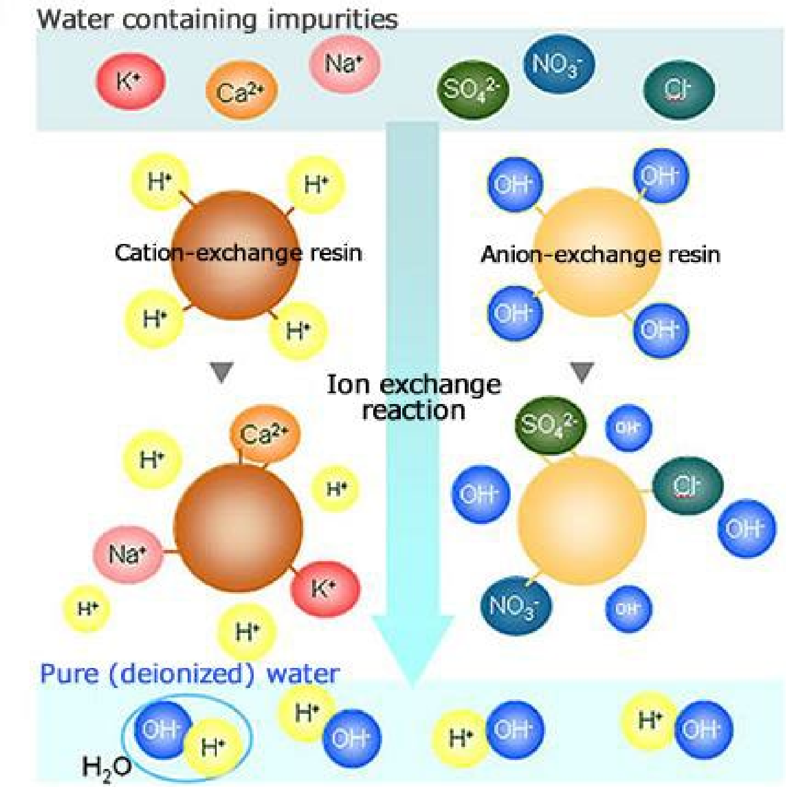
To avoid convection currents rolling up the Rn at the bottom of the tank, diffuser caps were installed in 2020 with an underwater robot.



Water purification

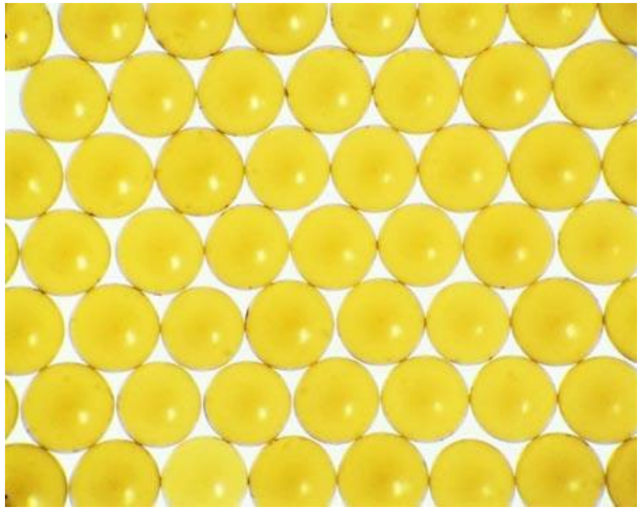
Gd sulfate could not be doped with the original SK water system designed to remove all the impurities other than H_2O.

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.



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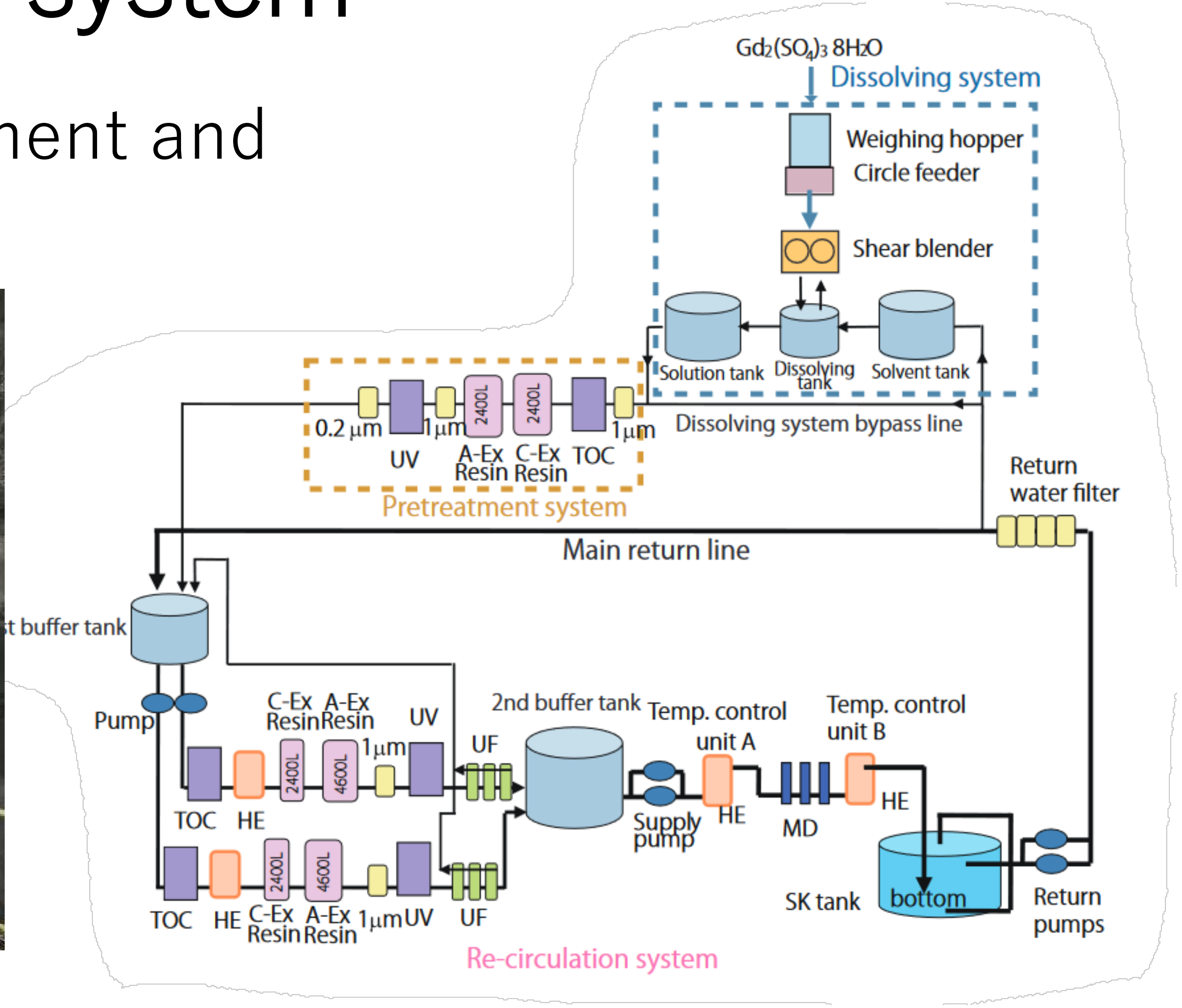
Pretreat + Recirculation system

- The resins are used for pretreatment and recirculation processes



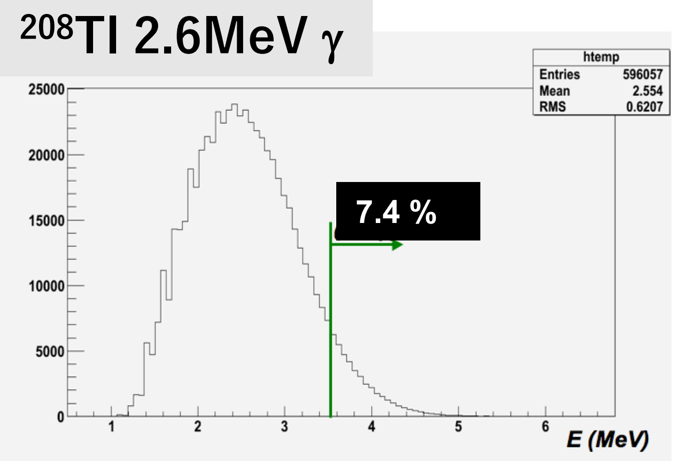
- The recirculation flow rate had been doubled to 120m^3/h

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

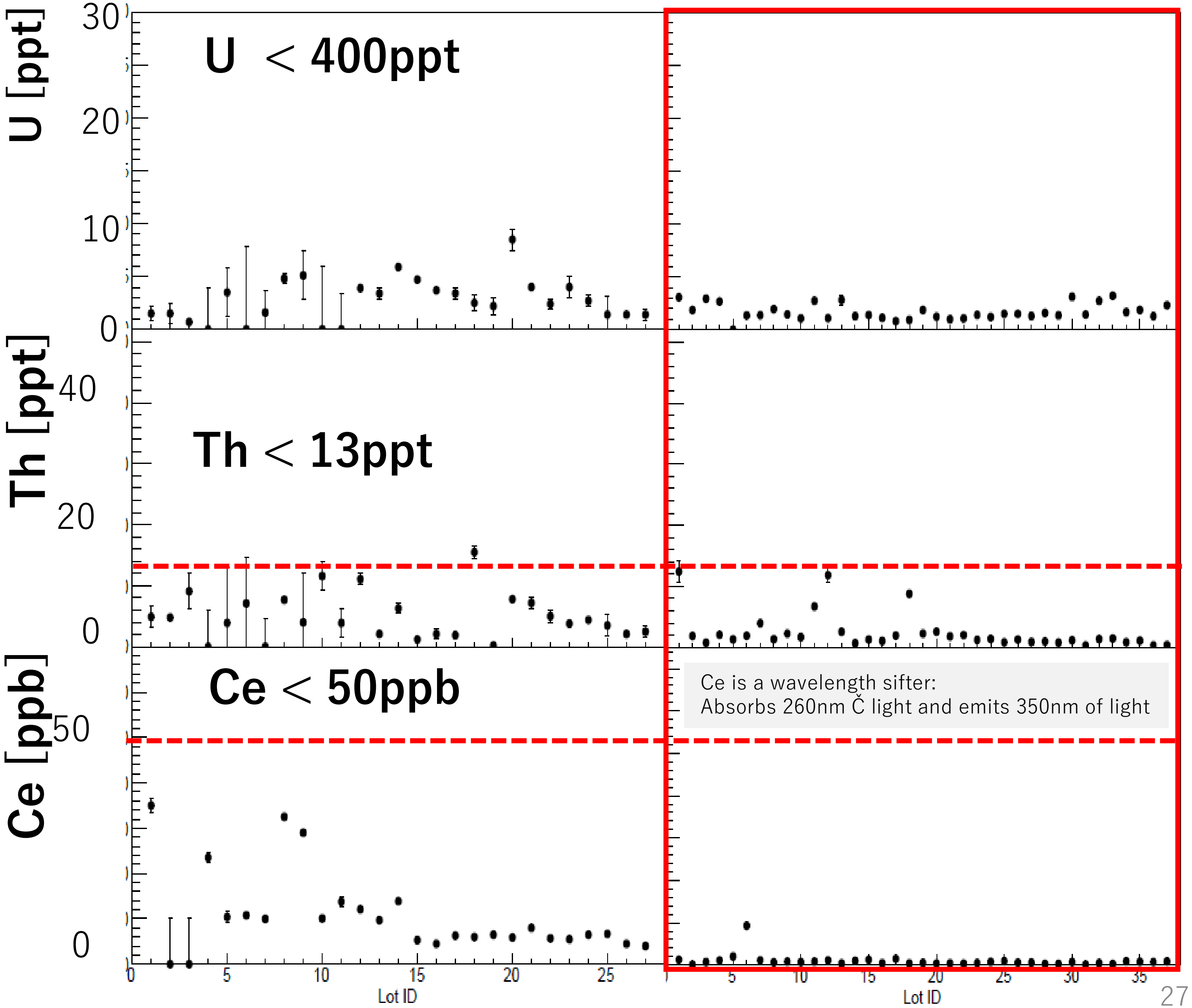
Purer Gd

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 65 production LOTs of the $Gd_2(SO_4)_3 \cdot 8H_2O$

Collaboration with

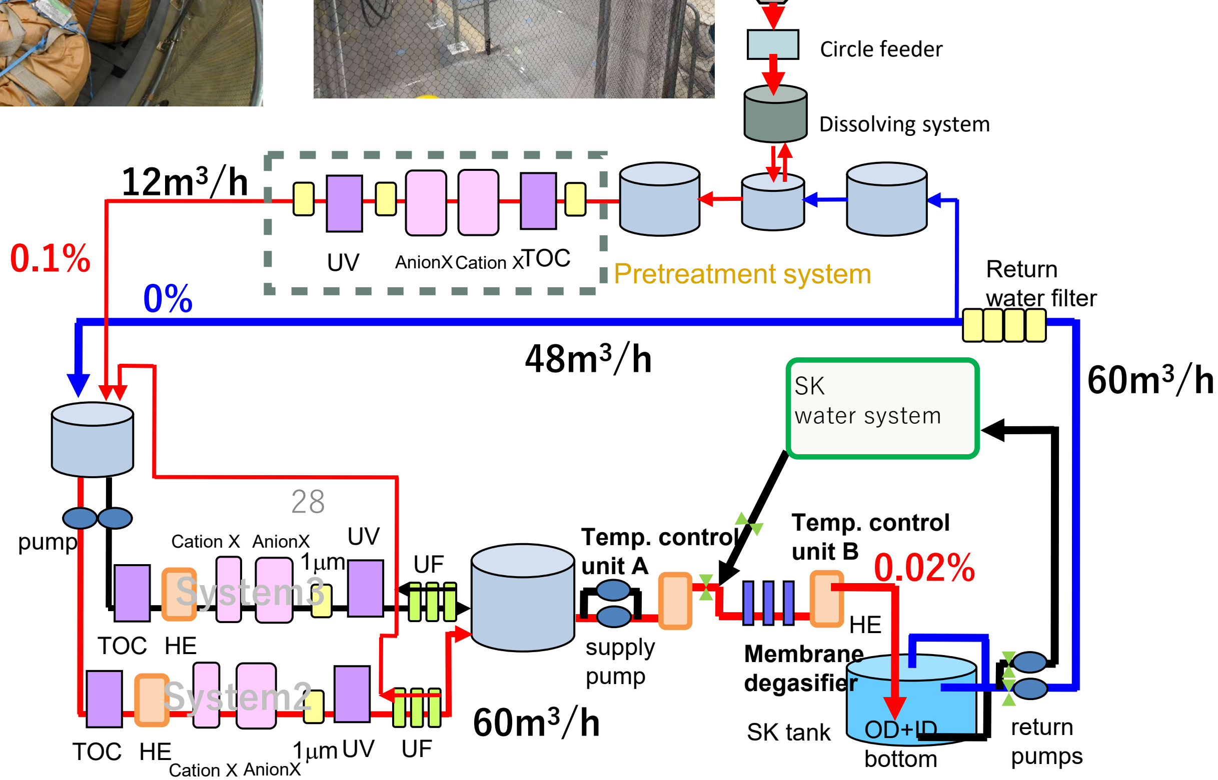
Kamioka ICP-MS result



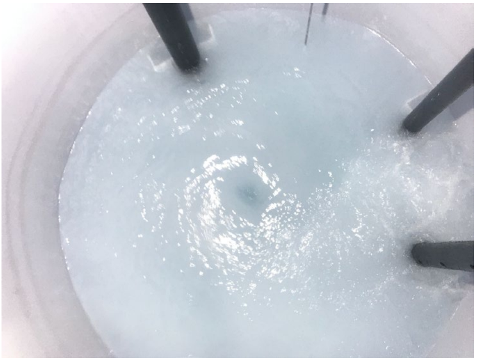
The 1st Gd-loading Jul. 14 – Aug. 18, 2020

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
For total of 13 tons:
Repeated every 30 minutes for 24 hours for 35 consecutive days



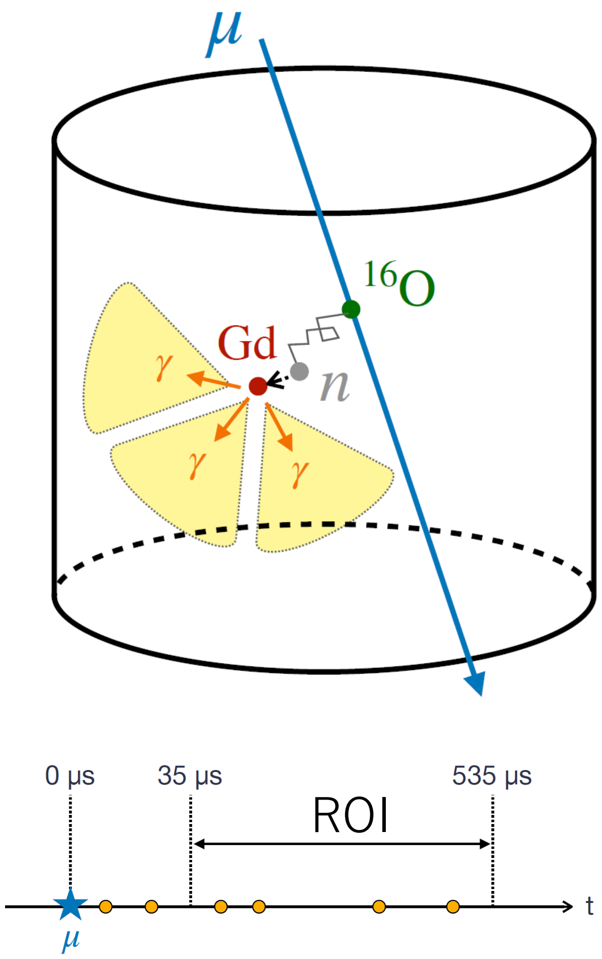
Just after mixing



10minutes later

Spallation neutron for Gd check

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



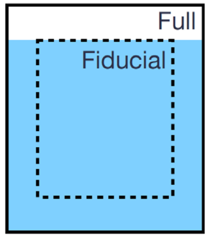
List of spallation products

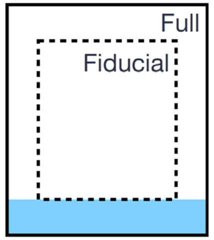
S.Li and J.Beacom,
Phys. Rev. C 89, 045801 (2014)

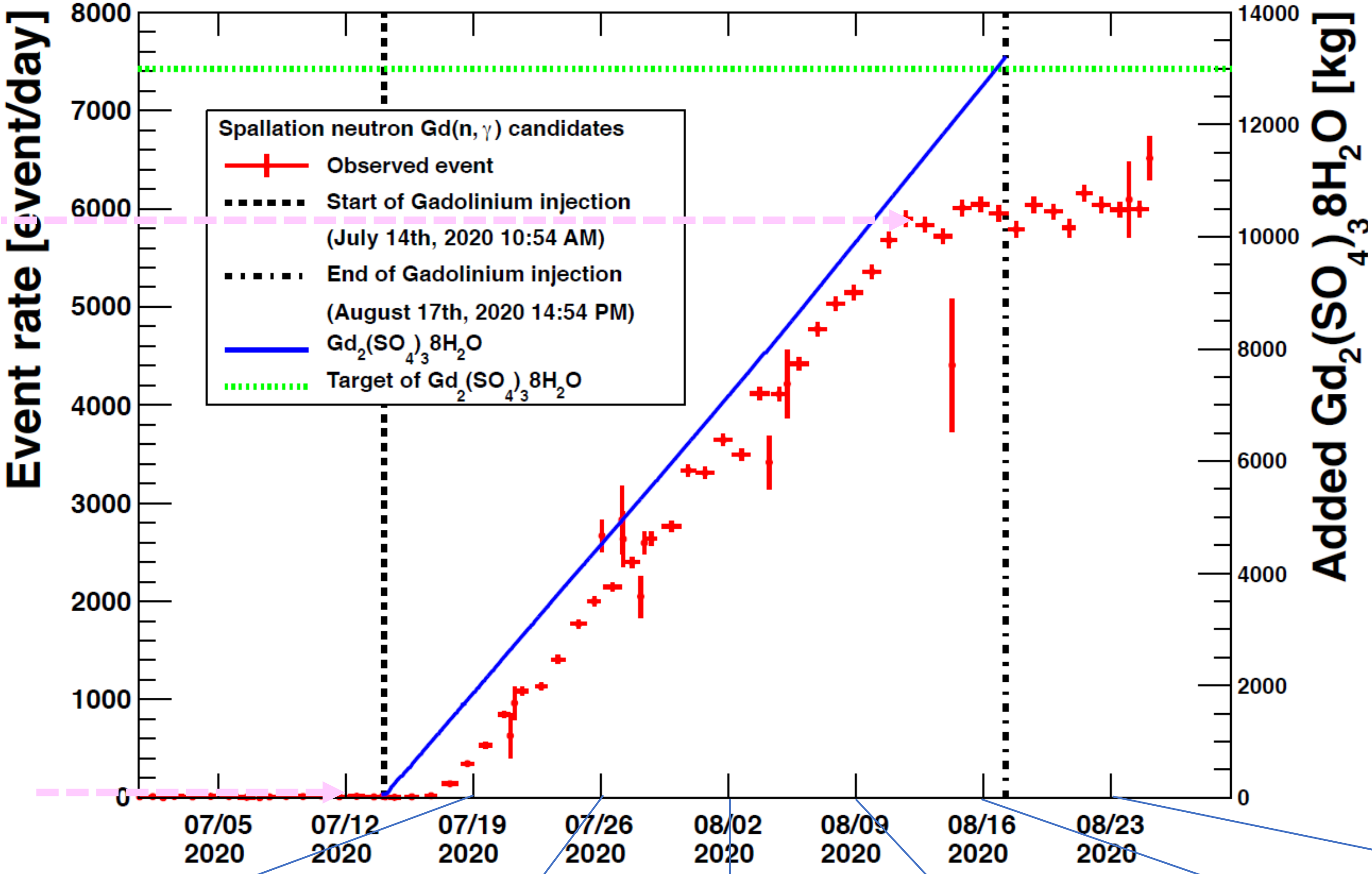
Isotope	Half-life (s)	Decay mode	Yield (total) ($\times 10^{-7}\mu^{-1}g^{-1}cm^2$)	Yield (E > 3.5 MeV) ($\times 10^{-7}\mu^{-1}g^{-1}cm^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	^{18}O(n,p)
^{17}N	4.173	$\beta^- n$	0.59	0.02	^{18}O(n,n+p)
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	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	

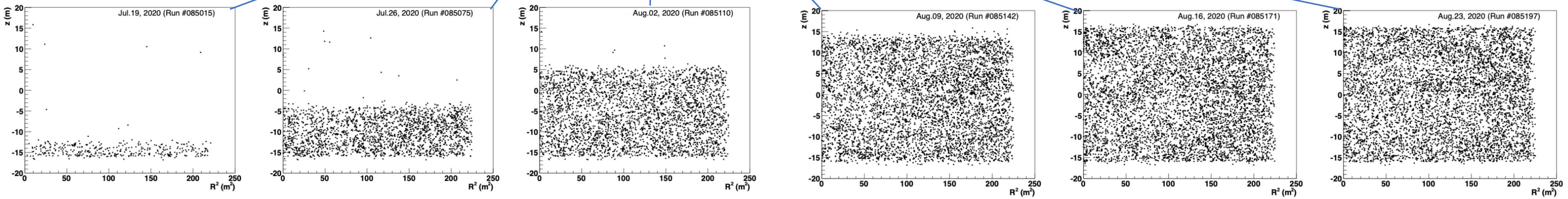
Neutron event rates vs. Gd-loading

Paper in preparation



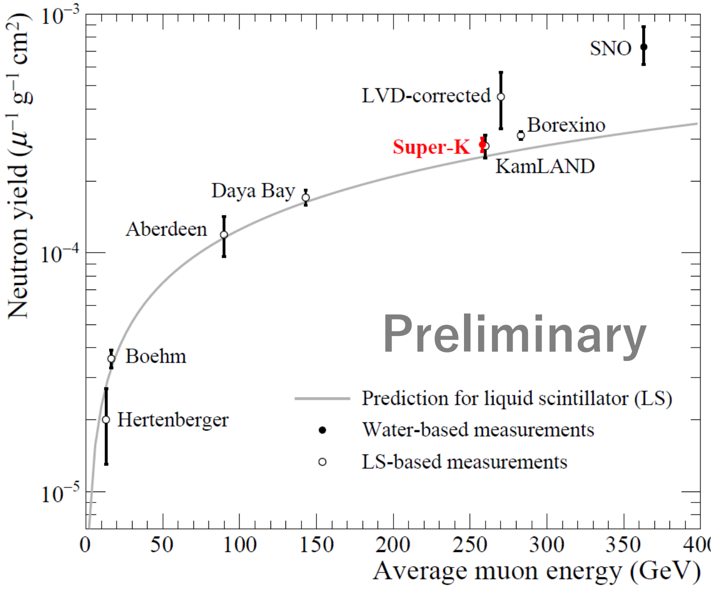






The result of neutron yield measurement:

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

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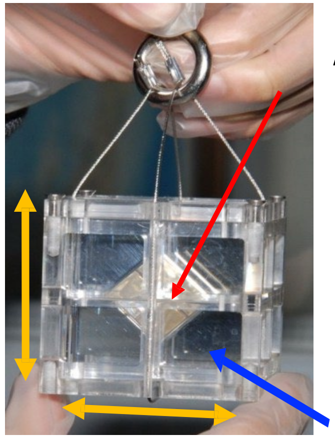
Gd concentration check after loading

- Neutron capture time is sensitive to Gd concentration.

Am/Be neutron source was deployed in SK



8 BGO Crystals

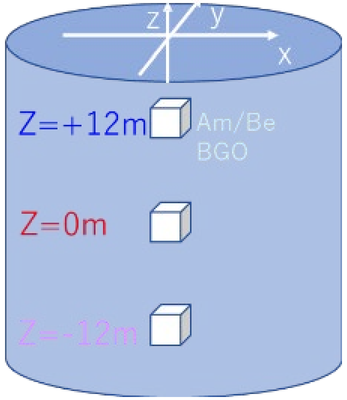
Am/Be neutron source

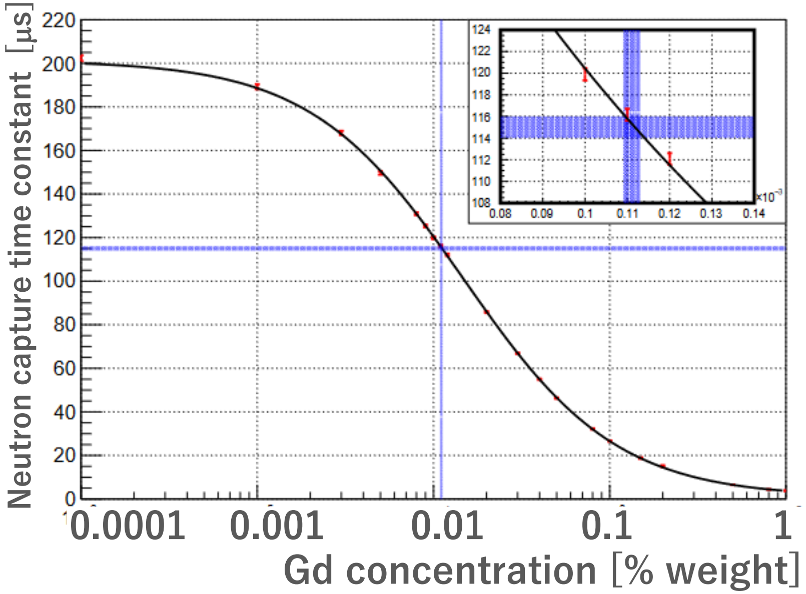
100~200 neutrons/s

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

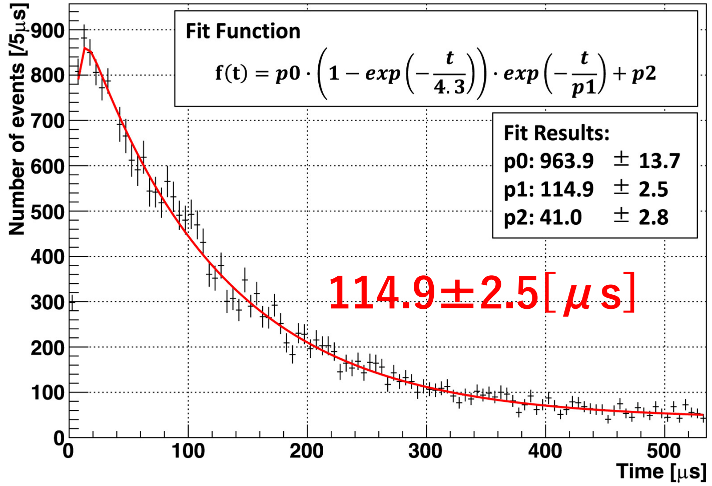
$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C}^{*} + \mathrm{n}$ (2-6 MeV)

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

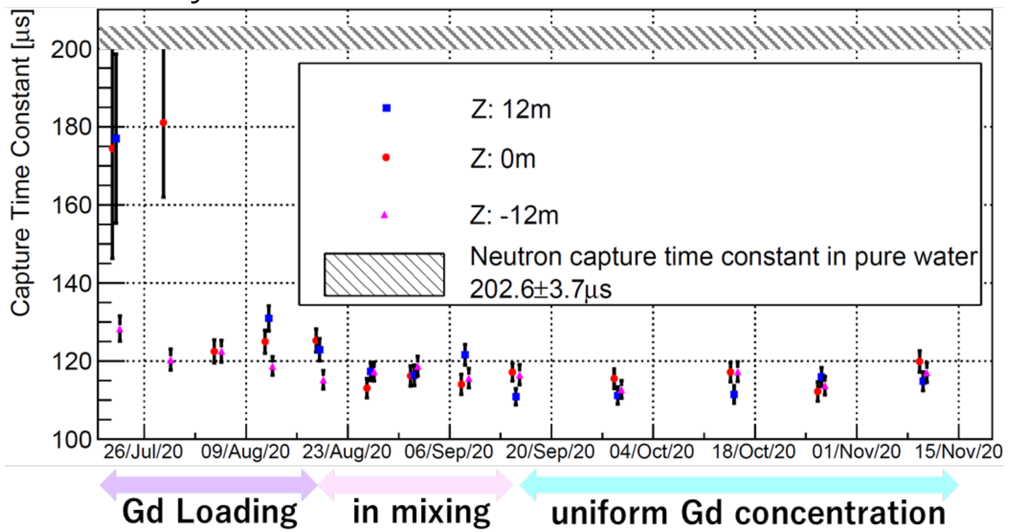




Time difference between scintillation and neutron capture γ-rays as of September 29, 2020



Every two weeks



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

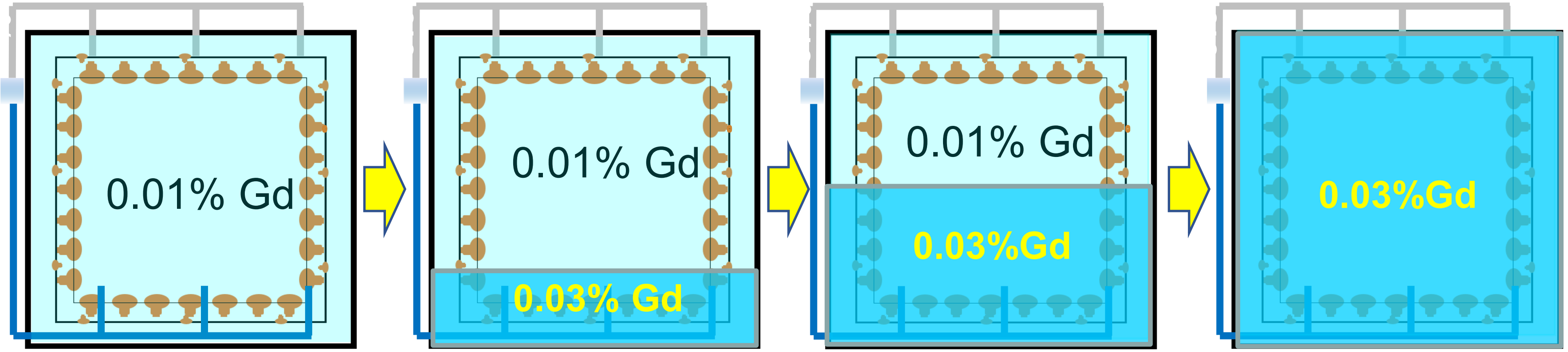
The 2nd Gd-loading Jun 1 – Jul. 5, 2022

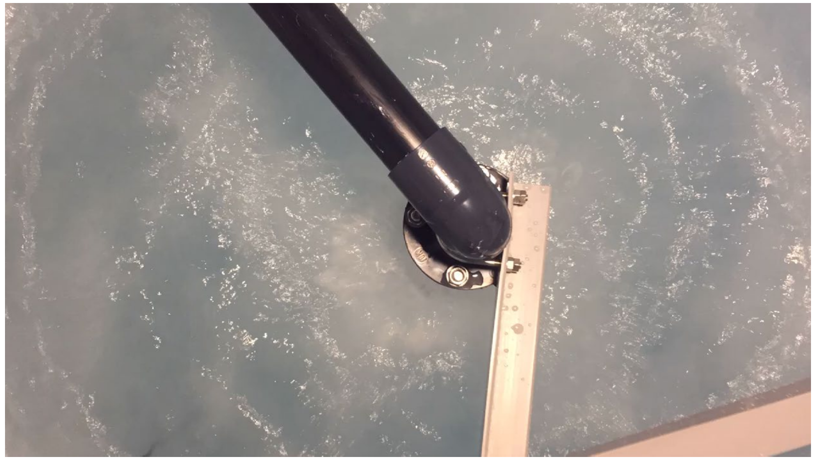
0.01% Gd water was taken from the top and returned from the bottom in **0.06% $Gd_2(SO_4)_3$** solution **(=0.03% Gd = 0.078% $Gd_2(SO_4)_3 \cdot 8H_2O$)**. It took 35 days to replace 50,000 tons of water at 60 m^3/h

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



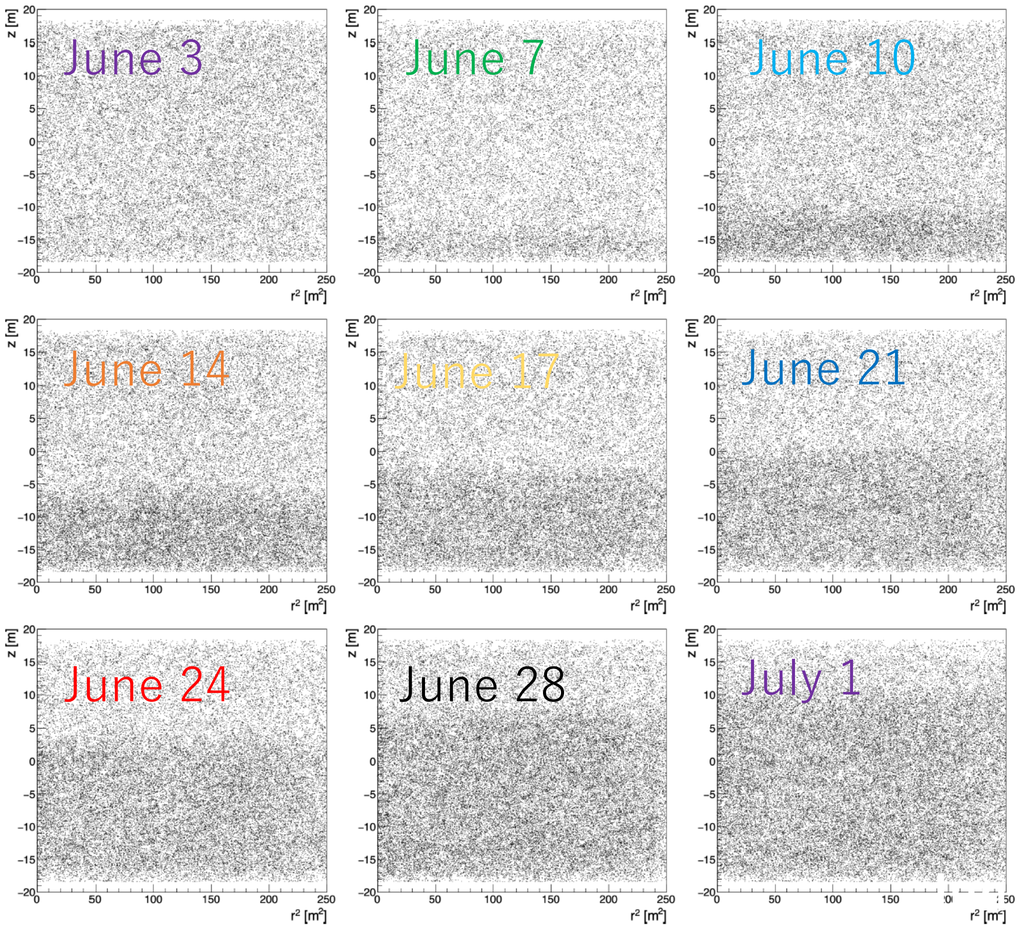


27tons
=1350 x 20kg cardboard boxes!

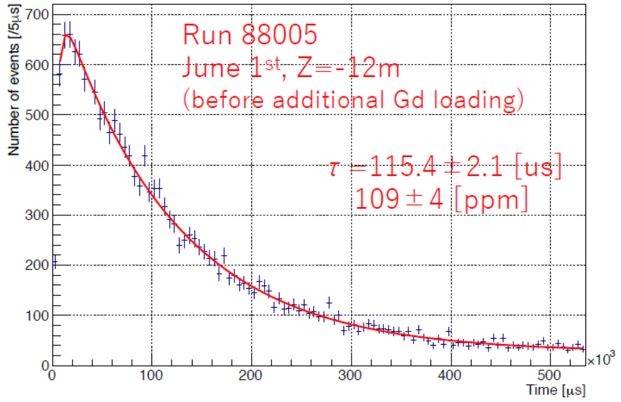
The 2nd Gd-loading

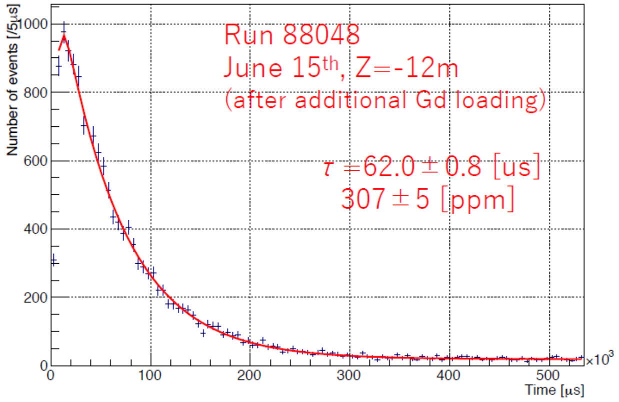
Preliminary

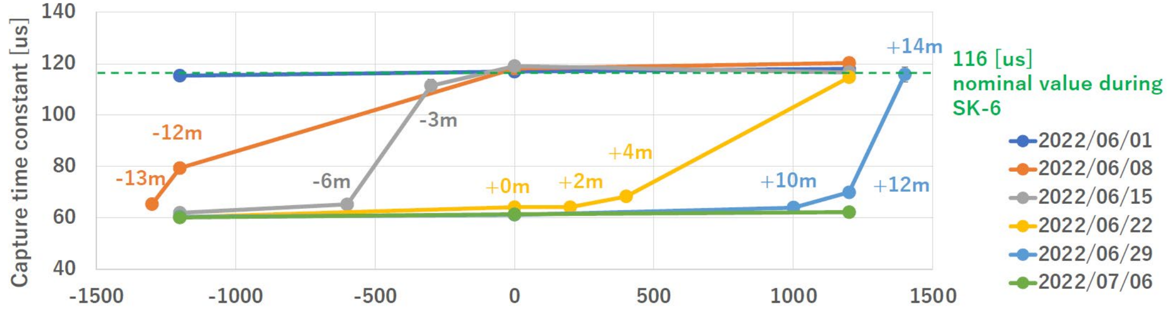
Spallation neutrons
1.5 times neutron capture efficiency was confirmed

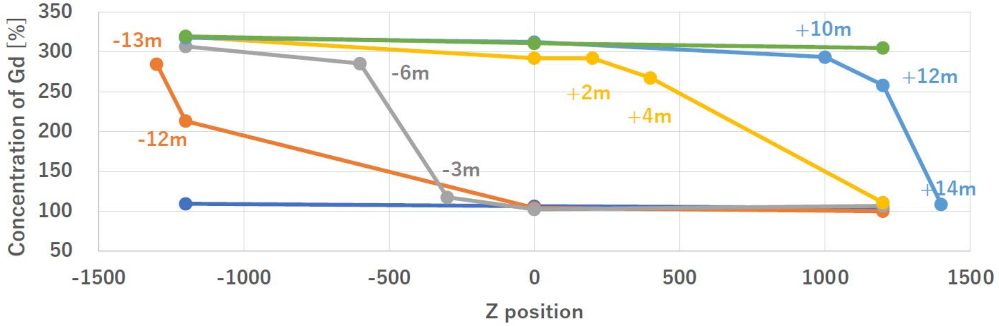


Am/Be neutron calibration
~310ppm was confirmed by the neutron capture time

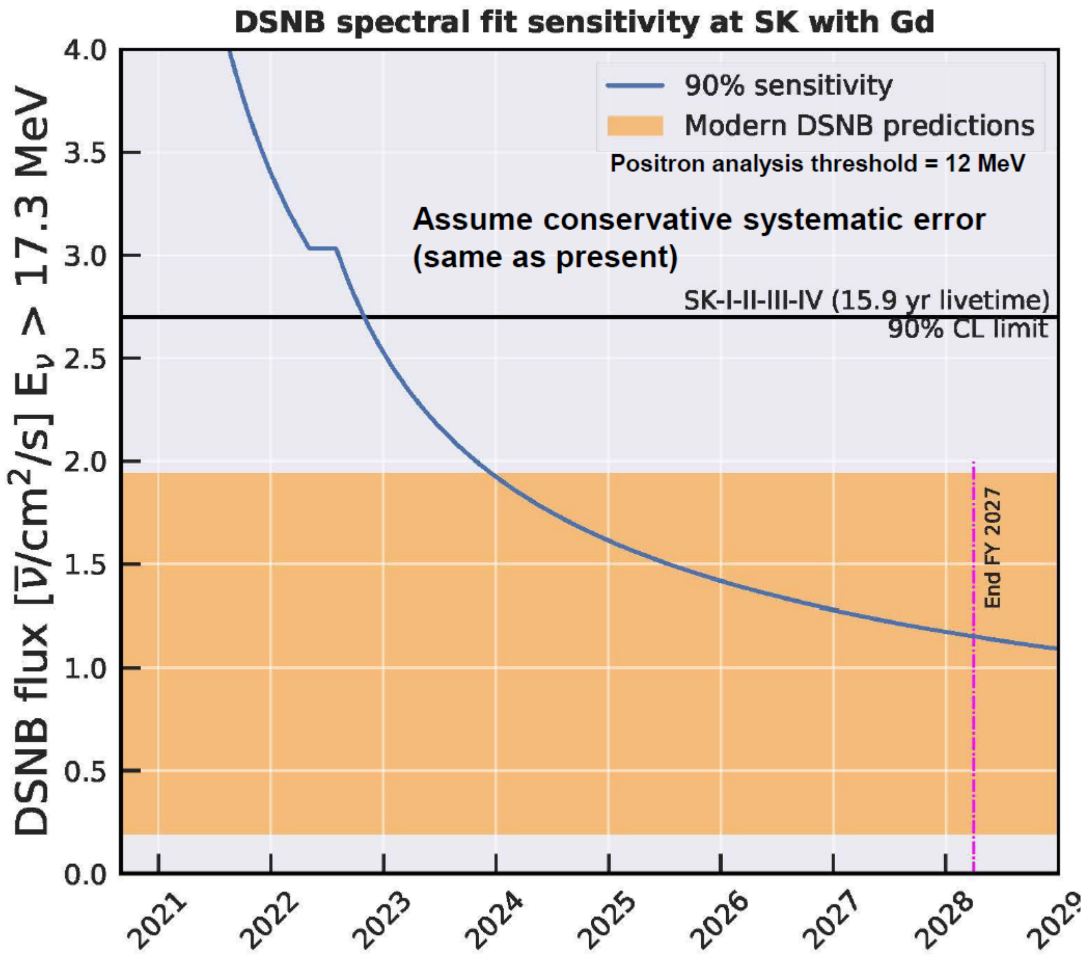




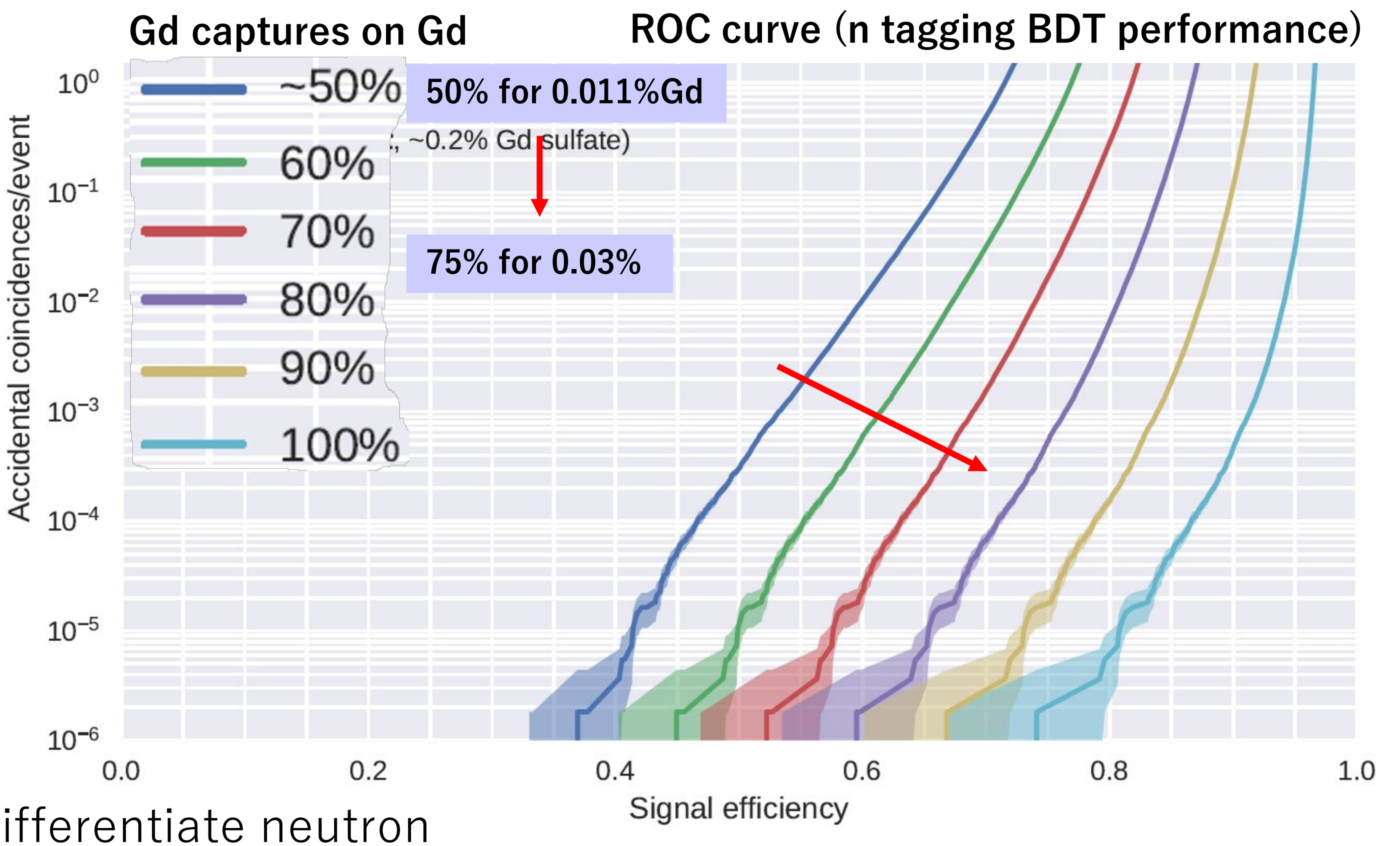




Expected sensitivity of SK-Gd with 0.03%

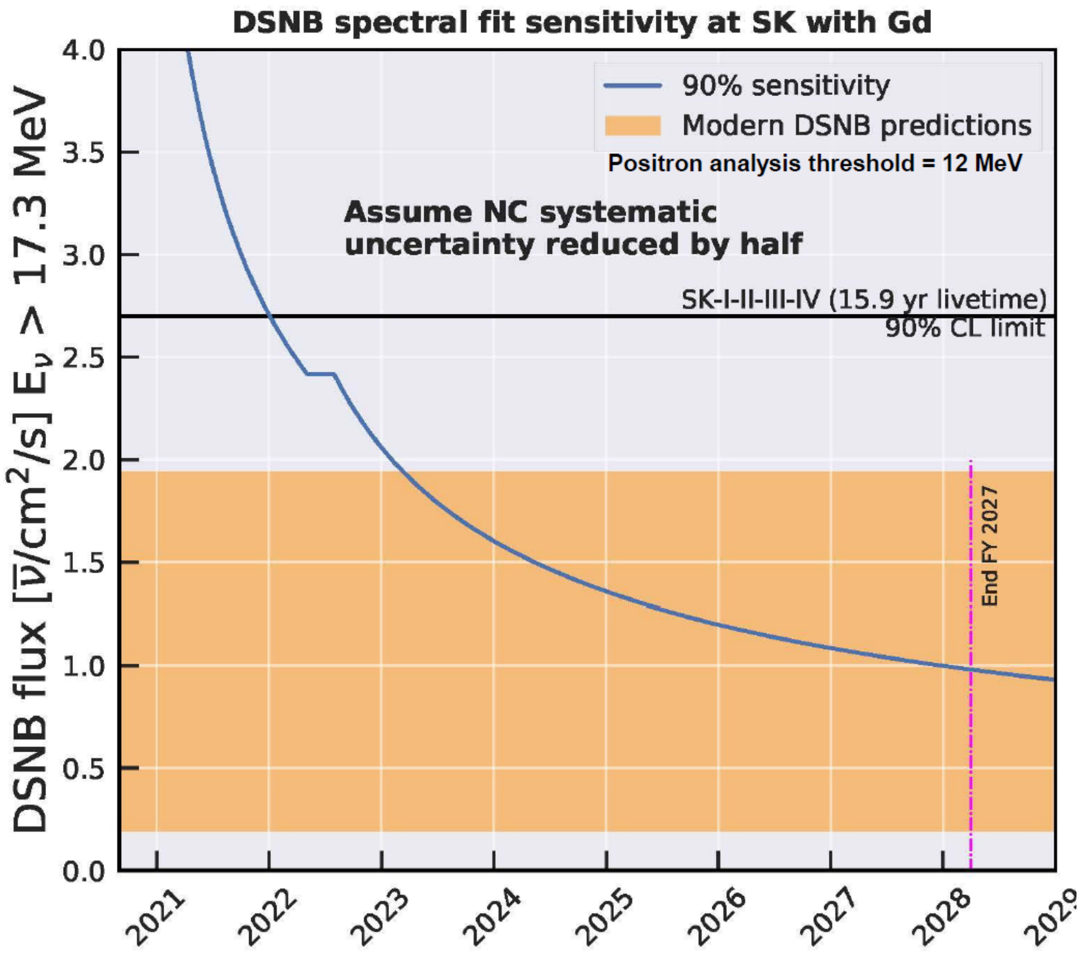


- Assume atmospheric NC background is the same as in SK-IV(very conservative)

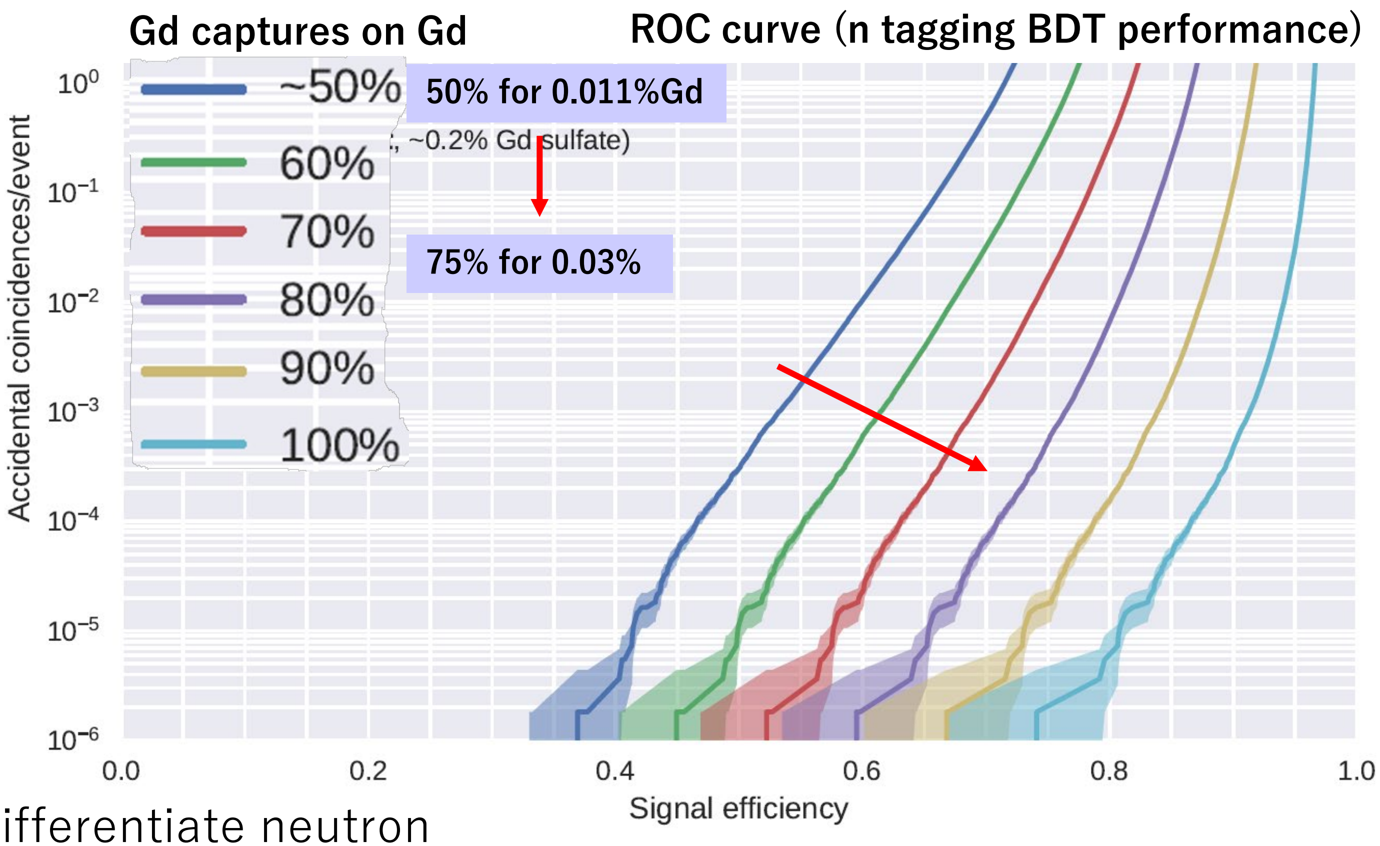


Further improvement: To what extent can we differentiate neutron capture signals from atmospheric NC interactions?

Expected sensitivity of SK-Gd with 0.03%

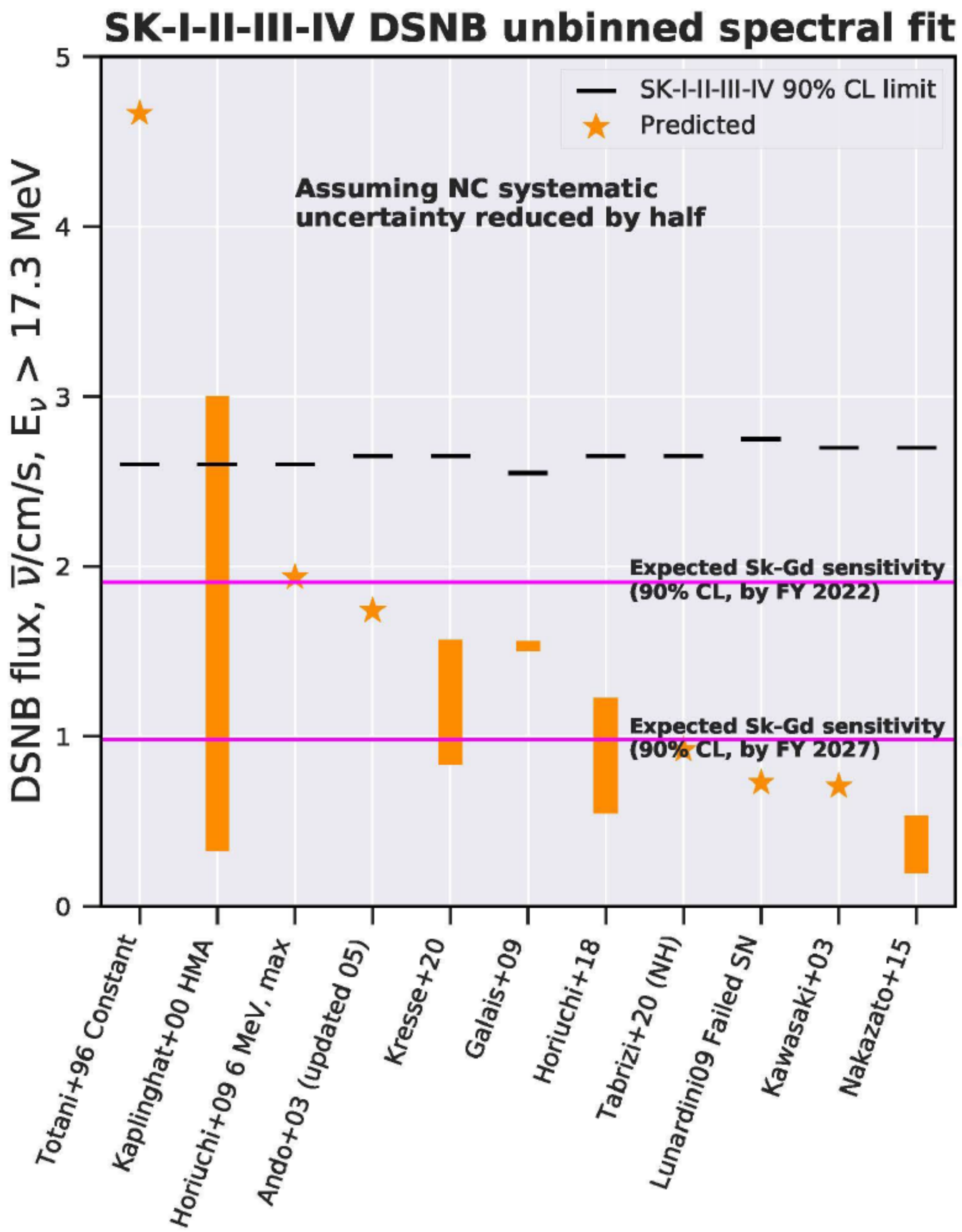


- Assume the uncertainty of the atmospheric NC background is reduced by half(still conservative)



Further improvement: To what extent can we differentiate neutron capture signals from atmospheric NC interactions?

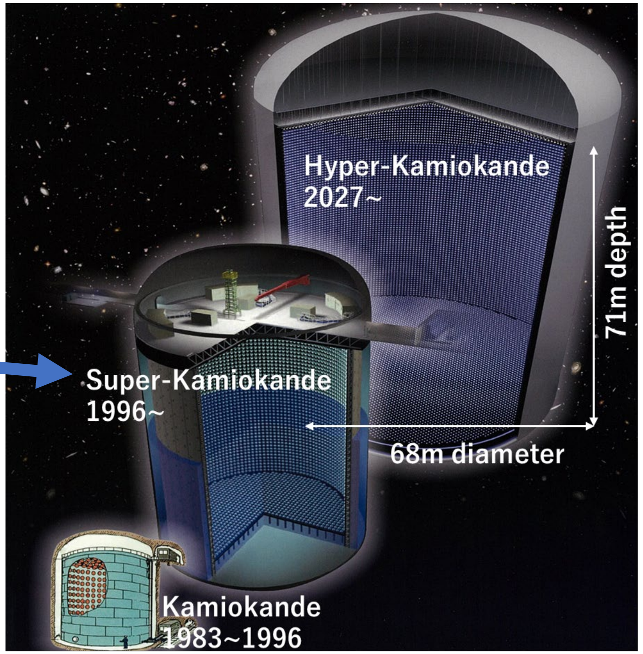
Constrains to each model



Summary

- Super-Kamiokande has been running since 1996 and achieved a world-leading sensitivity to the DSNB flux at 90% CL, comparable to the fluxes of several realistic models.
- SK has just moved to the SK-VII phase, achieving a concentration of 0.03%. The enhanced neutron tagging capabilities will allow us to set meaningful constraints on DSNB with the realistic prospect of a ground-breaking discovery.

Stay tuned to Super-Kamiokande!



Extra slides

Supernova burst neutrino

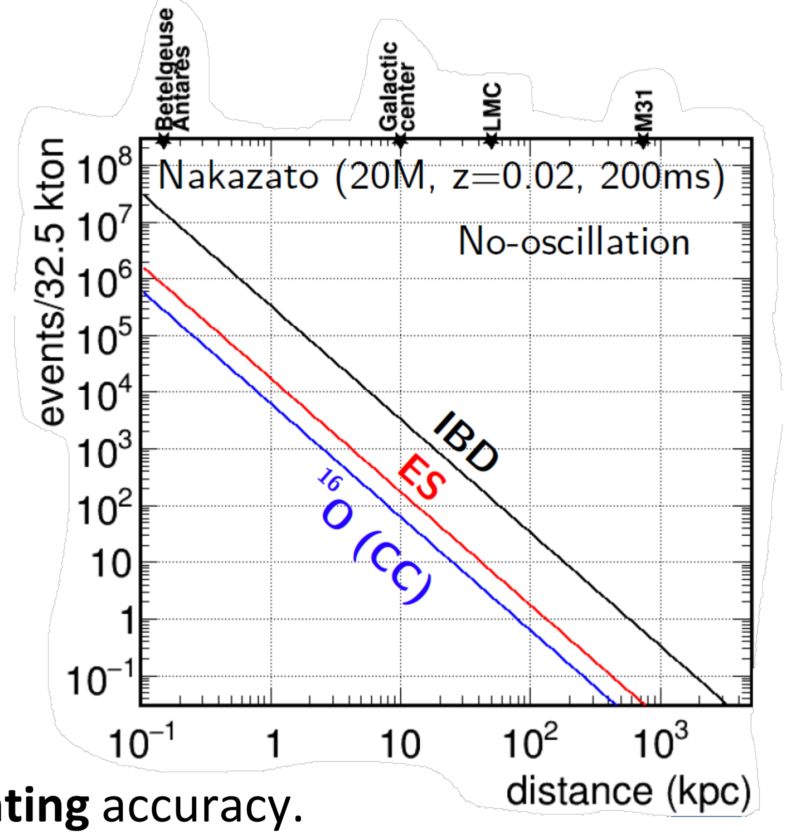
Super-Kamiokande can point the galactic SN direction via ES

Inverse Beta Decay reaction (IBD) ~90% $\bar{\nu}_e + p \rightarrow e^+ + n$

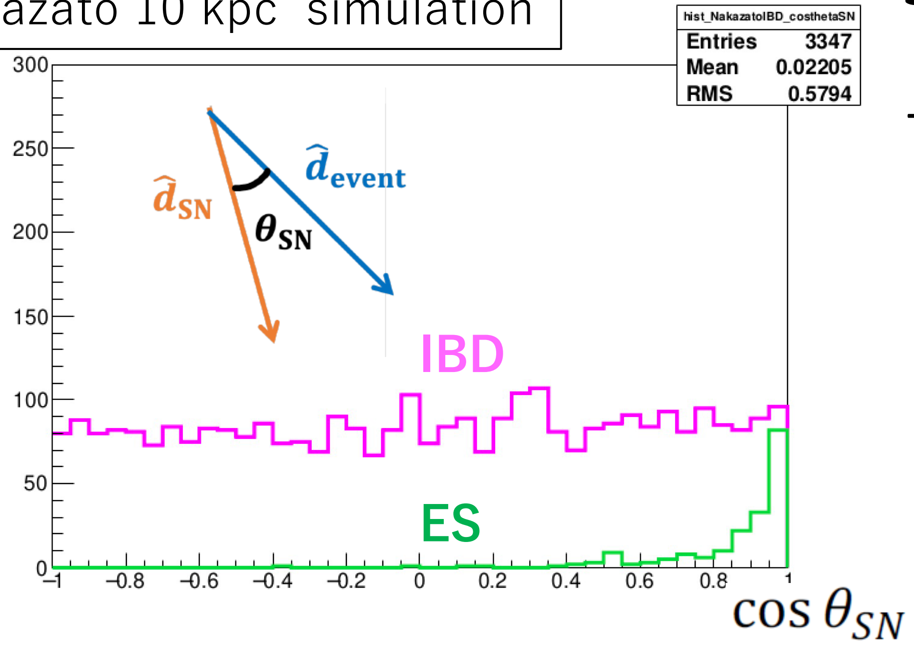
The direction of positron does not reflect the direction of the neutrino

Elastic Scattering interactions (ES) ~5% $\boldsymbol{\nu + e^- \rightarrow \nu + e^-}$

The electron keeps the neutrino direction information.

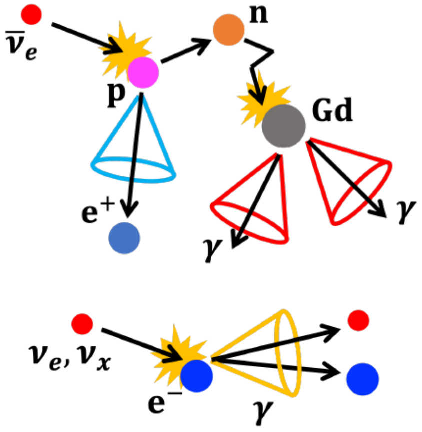


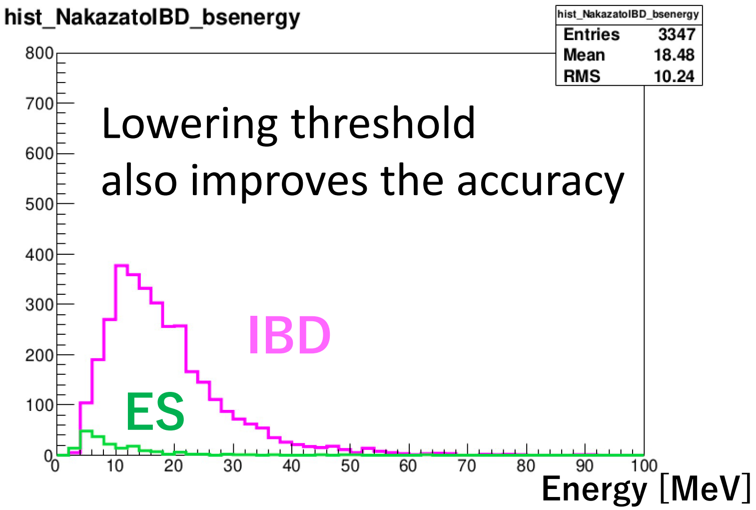
Nakazato 10 kpc simulation



Separating ES from **IBD** allows improving the **SN direction pointing** accuracy.

→ Gd enhances the IBS tagging





Expected pointing accuracy

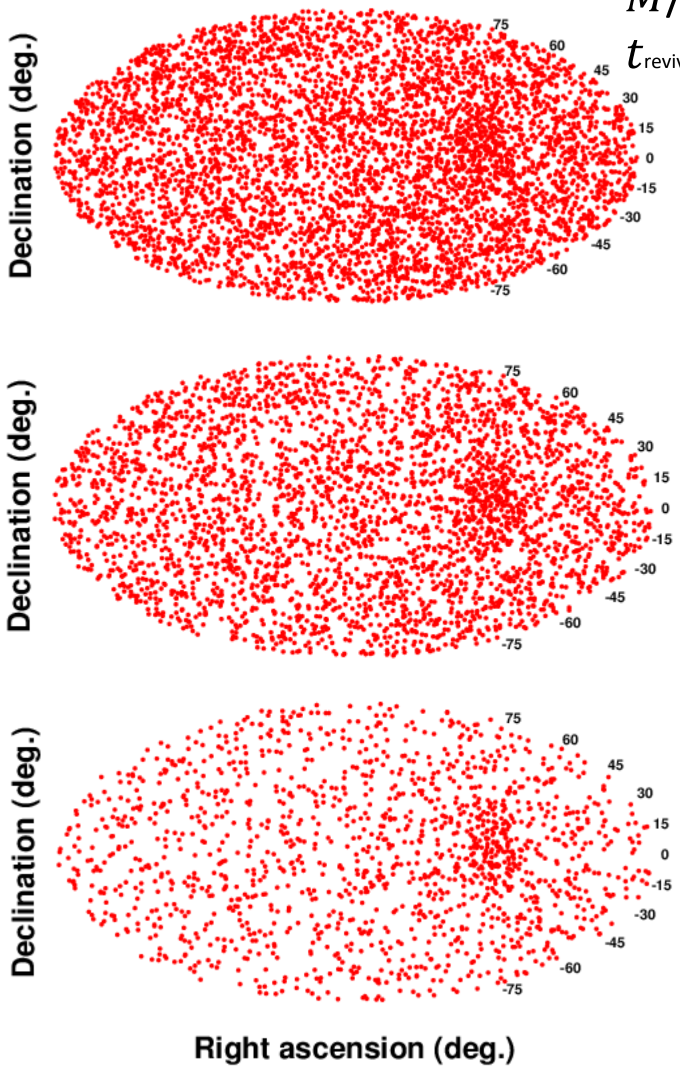
Extracted ES events (10kpc SN Nakazato)

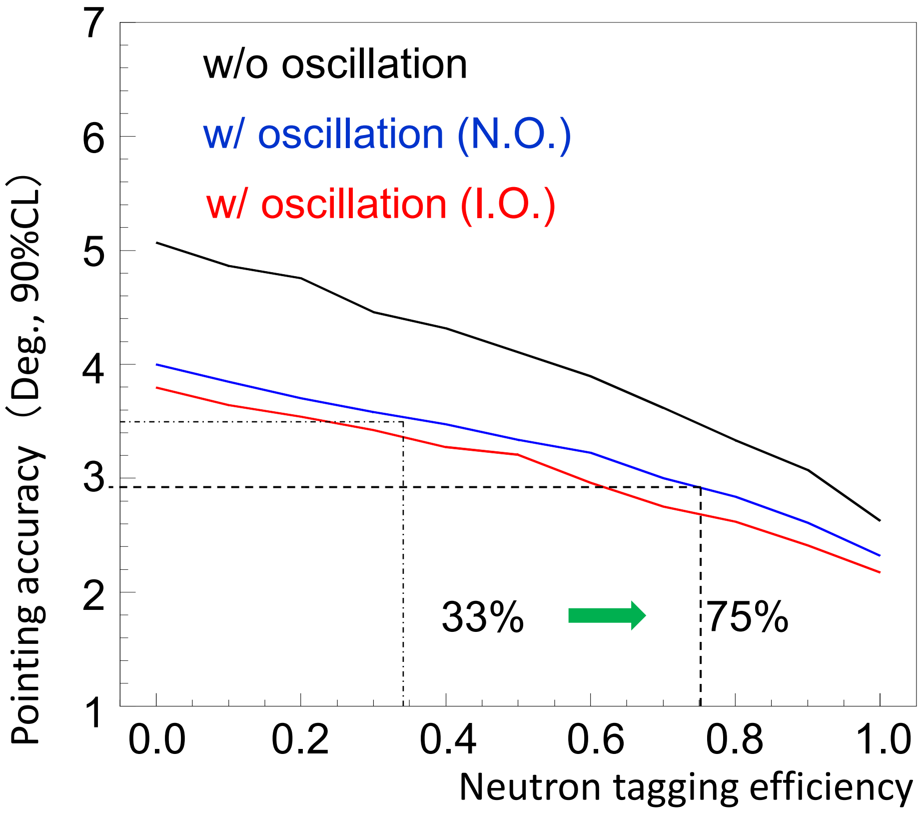
$M/M_\odot = 20$, $Z = 0.02 \sim Z_\odot$,
$t_{revive} = 200$ms

No Gd, SK-IV
Pointing accuracy
4deg (N.O. case)

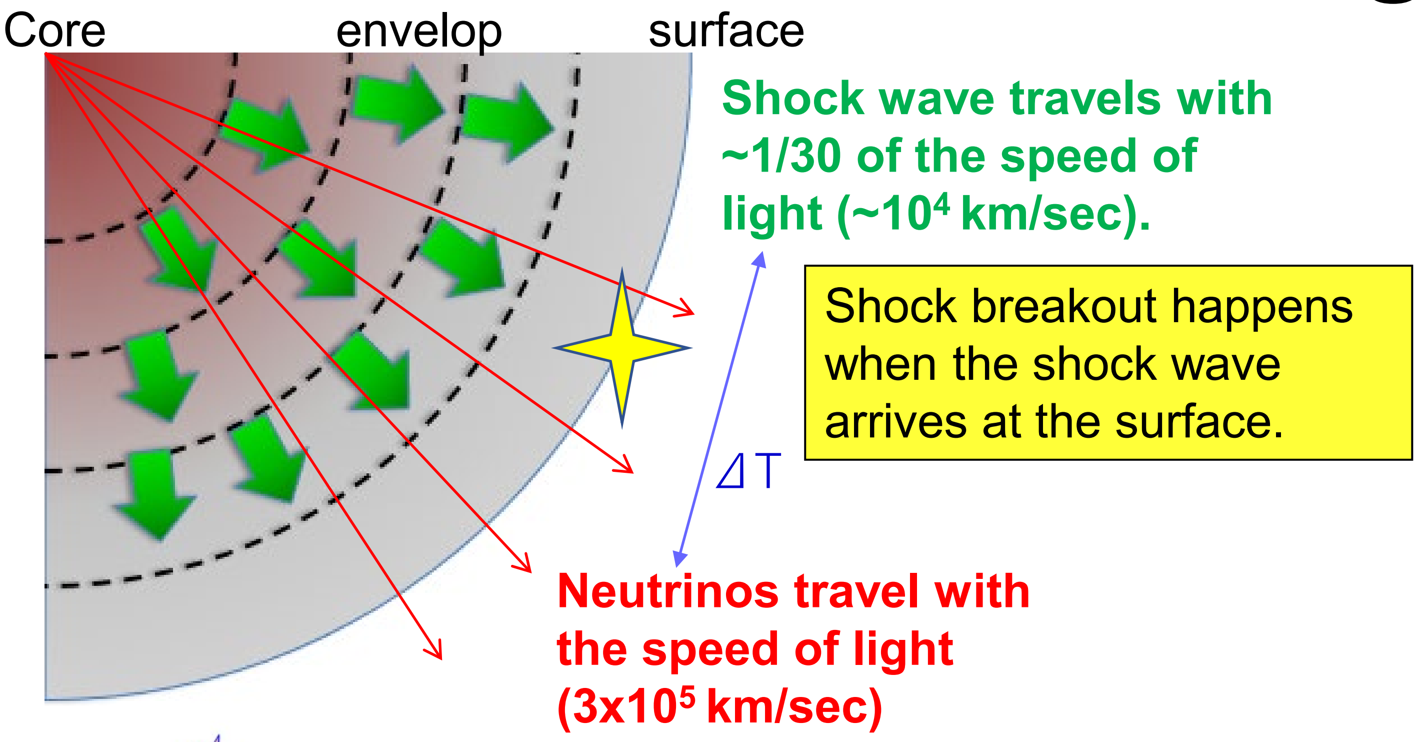
SK-VI 0.01%Gd
3.5 deg (N.O. case)
Search for the delayed sig.
with current threshold

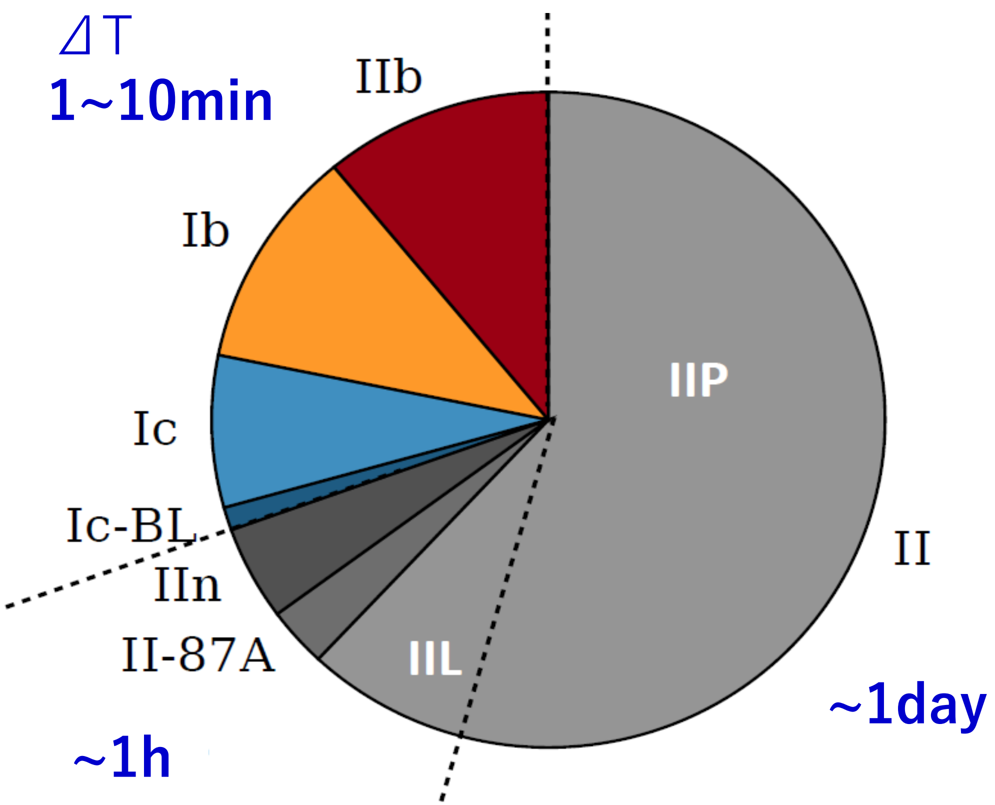
SK-VII 0.03% Gd
2.9 deg (N.O. case)
w/ Lowering threshold

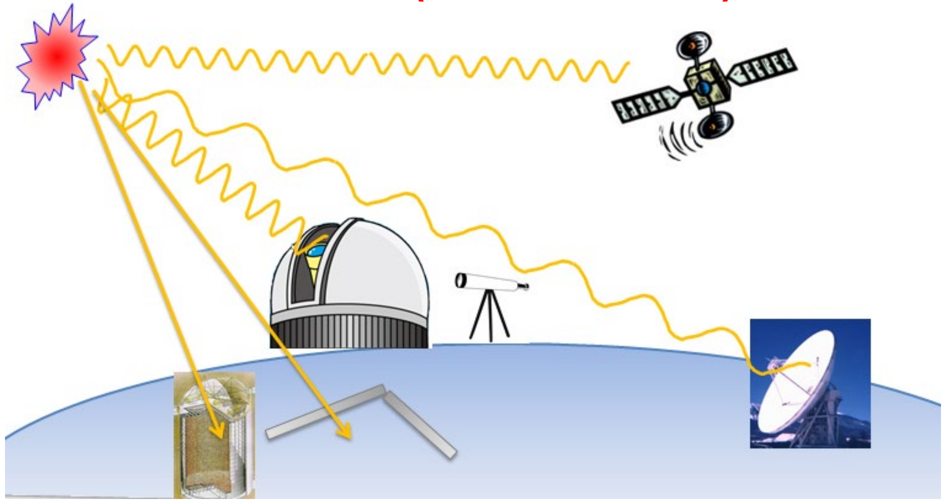




Role of SK in Multi-messenger astronomy







The time difference is several hours to tens of hours for ~70% of SNe and several minutes for others.

SK can send alerts to optical telescopes.

< 3 degrees is required
for FOV of Subaru, Simonyi Survey Telescope, etc.

Alert release time **Fast alarm is critical to observe the SN burst light.**

- Up to recently, it was taking a long time for SK to release an alarm;
  - Event reconstruction ~3 min for 10 kpc SN (~10 min for 3 kpc)
  - Experts meeting to decide to release an alarm and send the alarm.

→ On average, ~1h was needed to send the alarm(and miss 30% of optical SNe.)

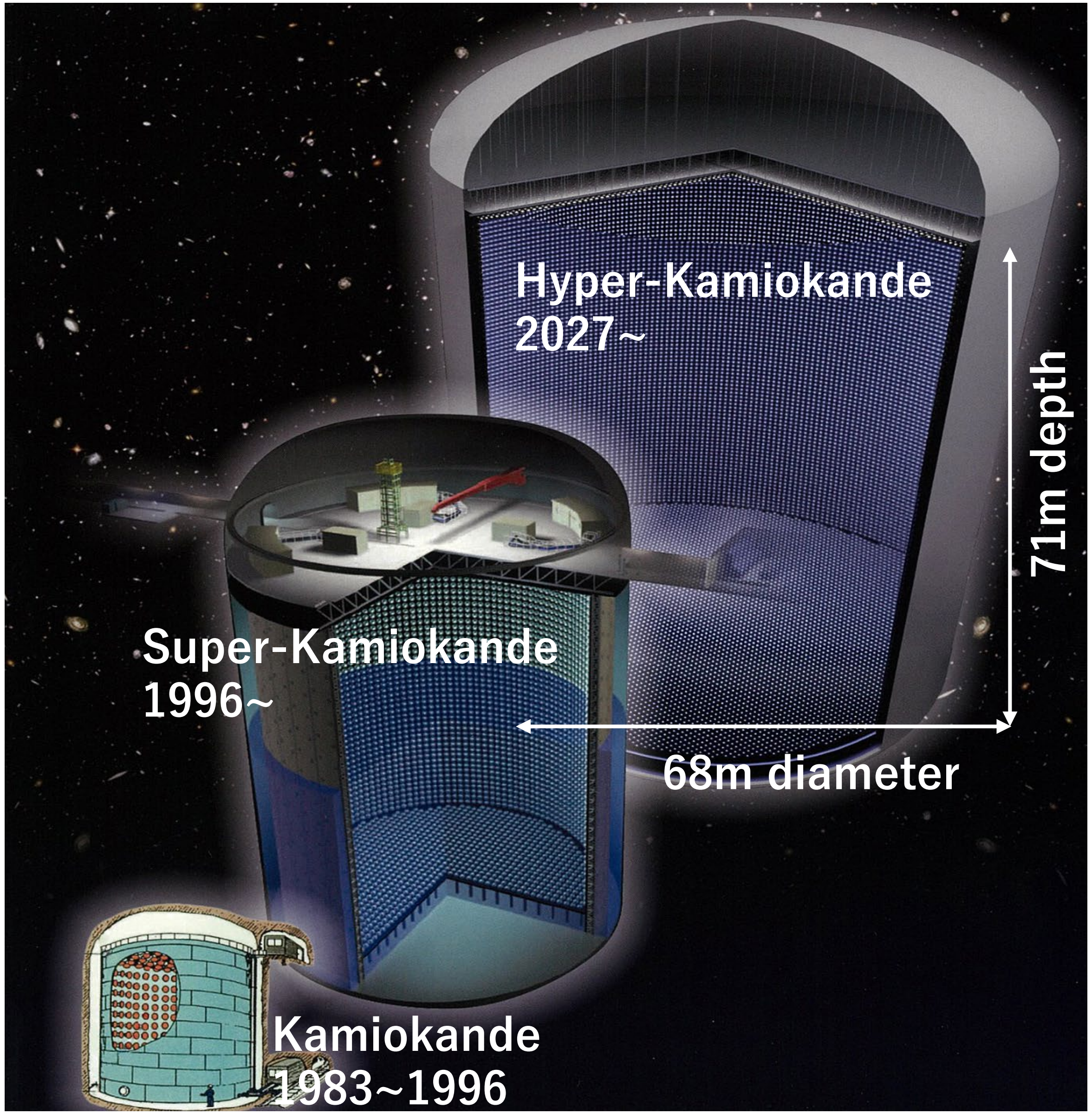
- Software and algorithm upgrades using multi-threading
  - Event reconstruction: <**1 min for 10 kpc SN** (~5 min for 3 kpc SN)
    - Further quick Healpix-based (from WMAP, Plank) SN direction finder is under investigation.
      → Preliminary results indicate ~2 sec for 10 kpc SN (<5 sec for any SN)
  - **Automated alarm to GCN-notice** shortly after the SN direction reconstruction

→ The alarm is expected to be released in about 1 minute following the Galactic SN. (Preliminary)

https://gcn.gsfc.nasa.gov/sk_sn.html

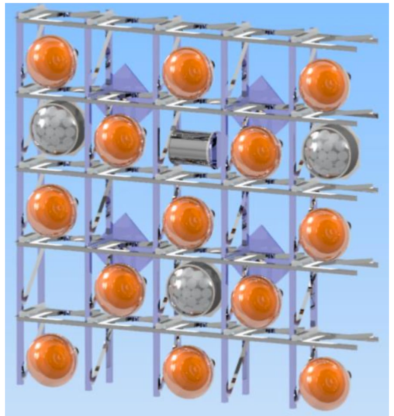
Hyper-Kamiokande Project

- Next generation giant water- Cherenkov detector with 258 kt ultra-pure water, provides 188 kt FV
  - **8 times larger than SK.**
- Inner detector (ID)
  - 20,000 of 20” PMT & a thousand multi-PMT
  - 20% and more photocathode coverage
- Outer detector (OD)
  - 3” PMT and wavelength shifting plates



Hamamatsu R12860
QE 2 x SK’s PMT

mPMT
19 x 3-inch PMT



The Hyper-Kamiokande Collaboraation

- 20 countries, 98 institutes, ~500 people as of 2022

Collaborating Institutes

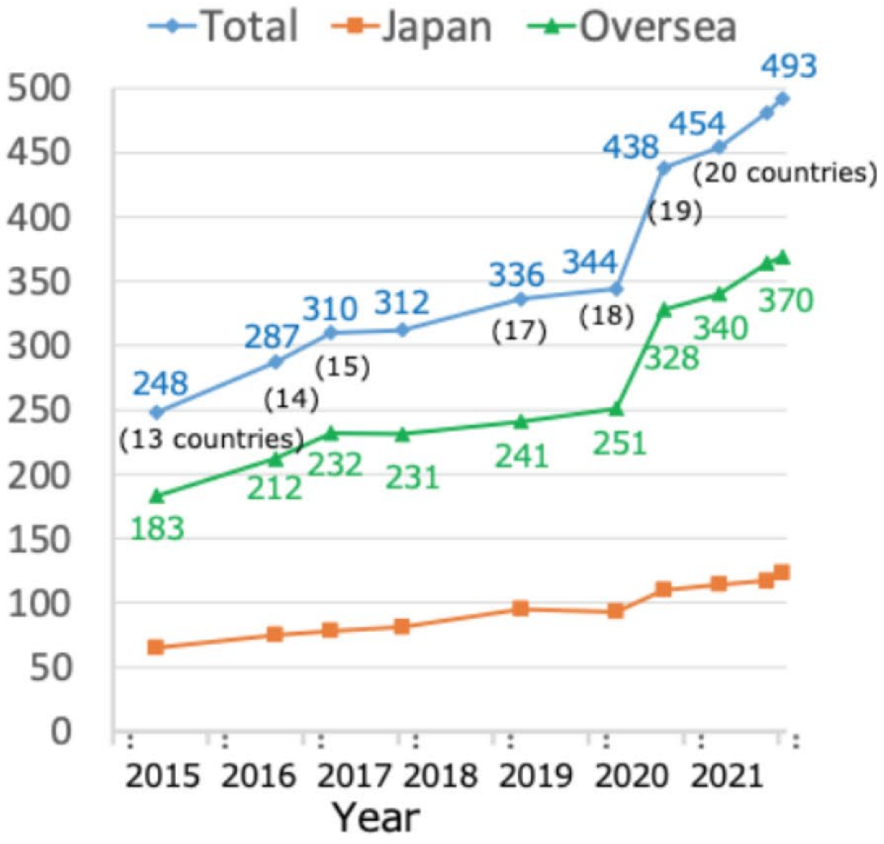
Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

Africa	11 members
Morocco	11

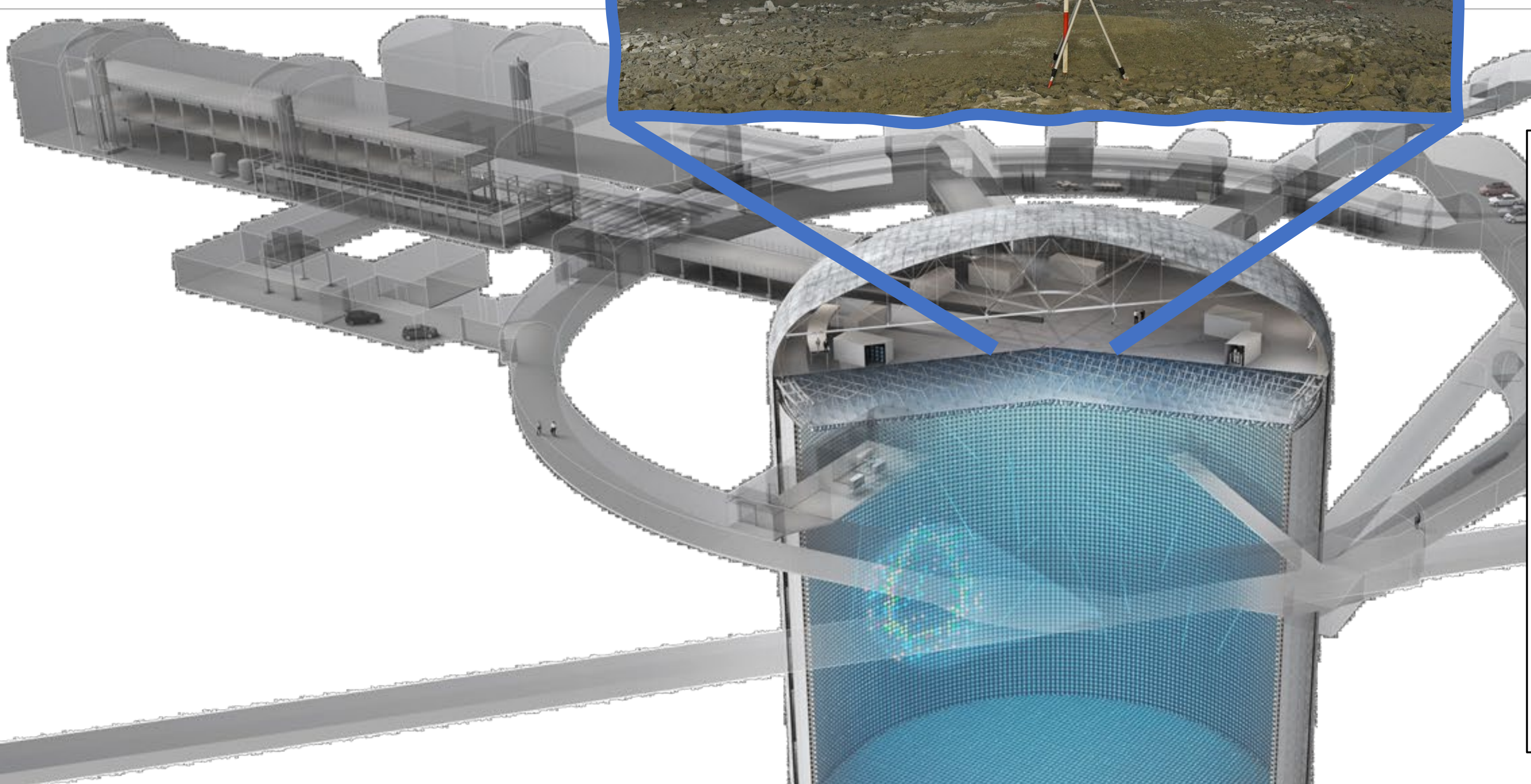
Number of collaborators



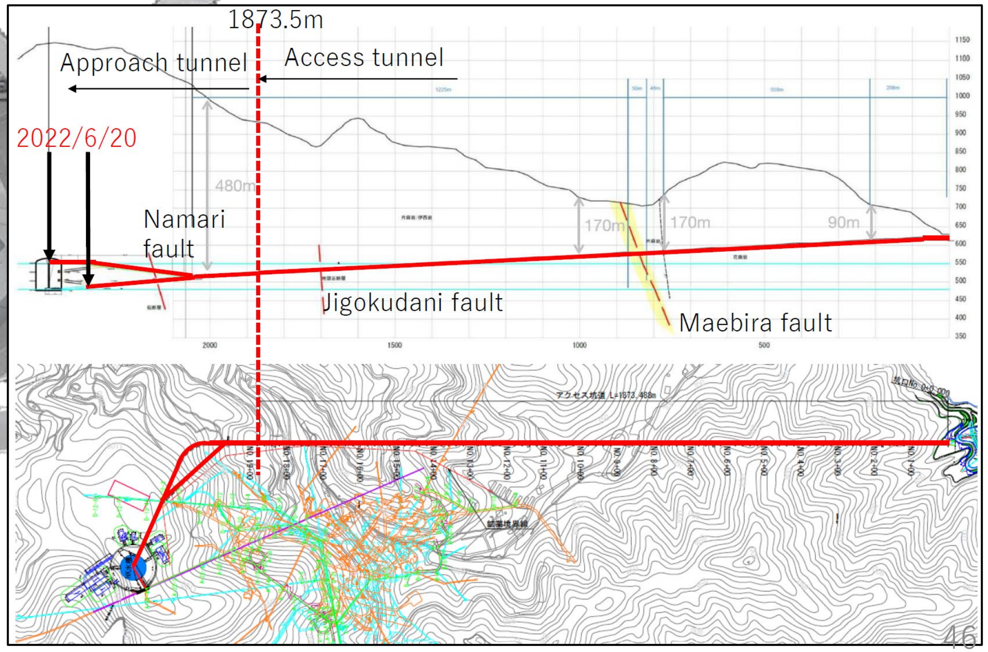
8km south from Super-K

- 295km from J-PARC: same off-axis angle as SK
- 650m rock overburden

The tunnel reached the center of the HK dorm

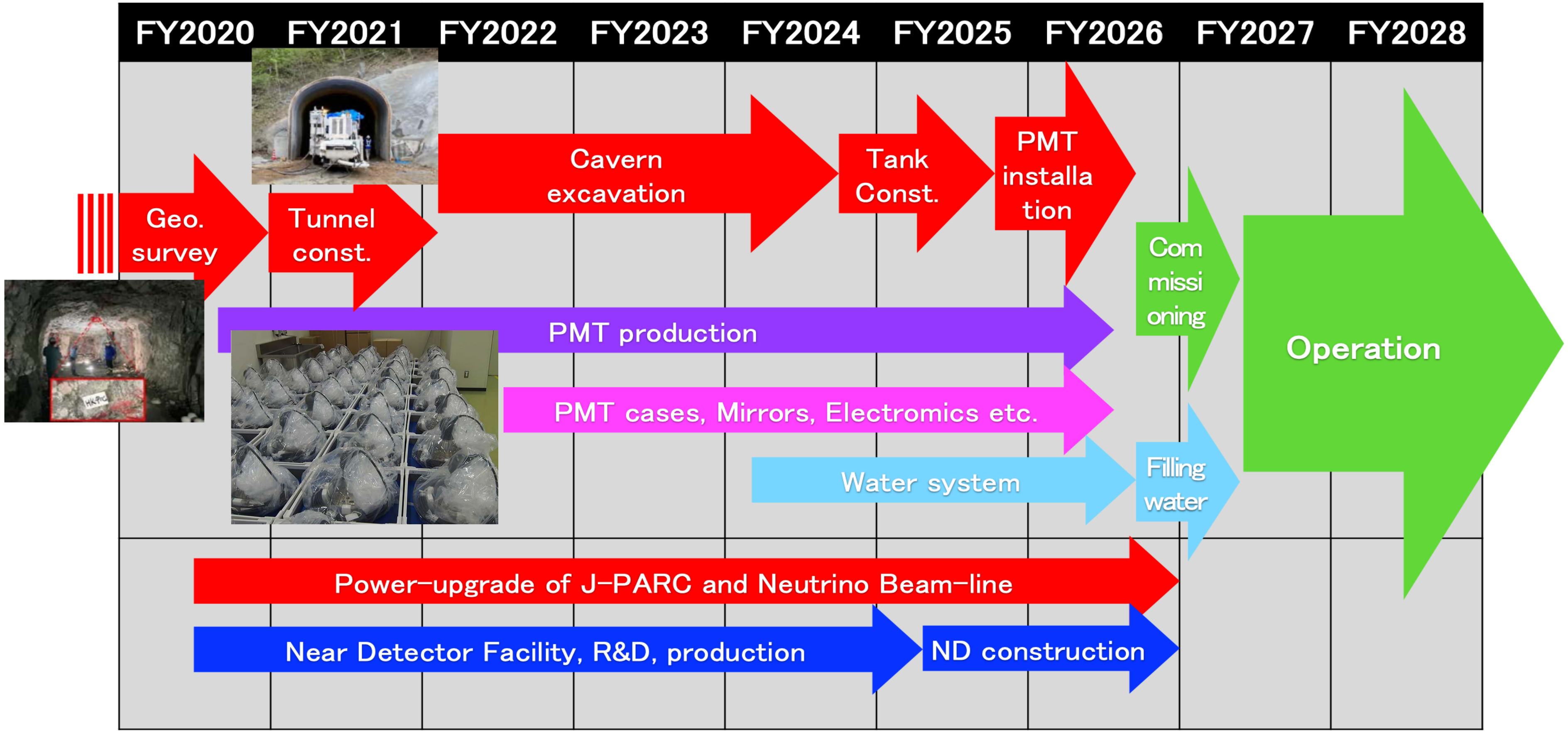


June 23, 2022

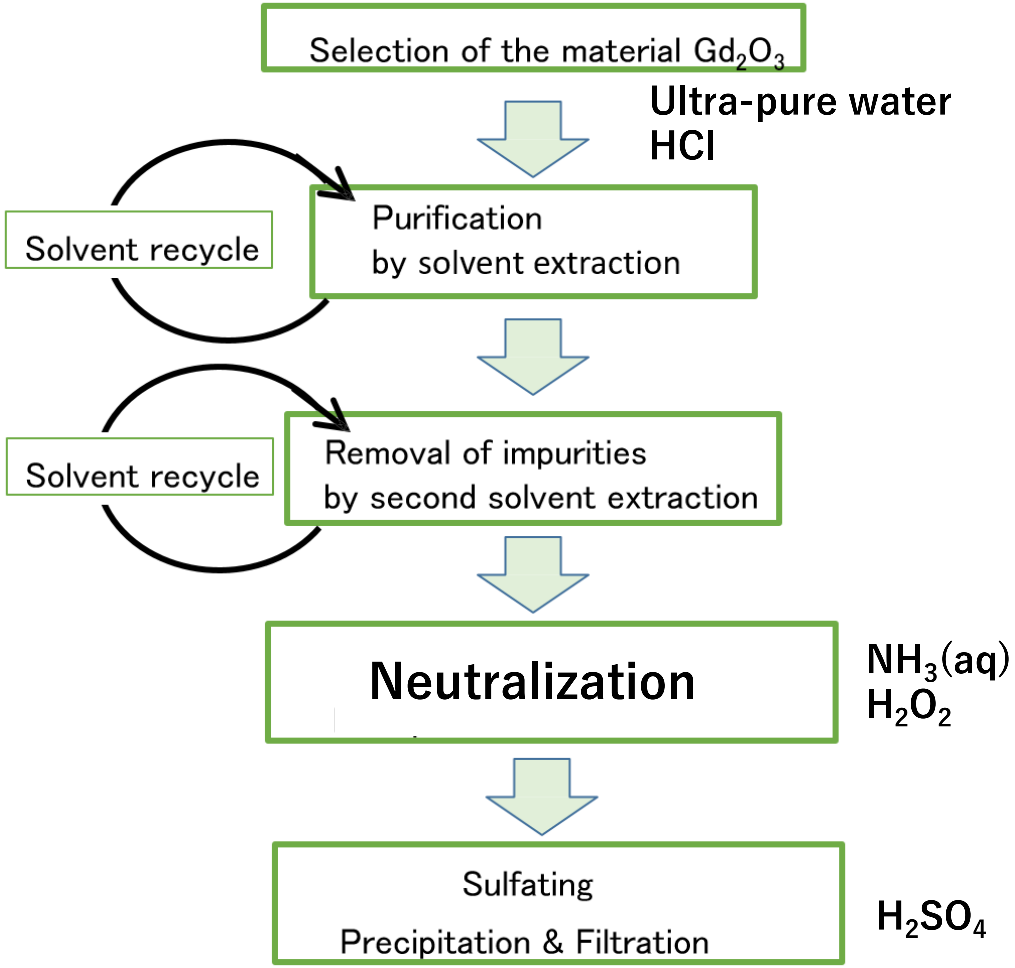


Project timeline

- 2020: project officially started
- 2021: Tunnel excavation started; 20” PMT mass production started
- 2022: Tunnel completed, and cavern excavation follows until 2024
- Tank construction in 2024-2025, followed by PMT installations in 2025-2026 and water filling 2026-2027
- Operation will get started in 2027.



Preparation of 40 tons of ultra pure $Gd_2(SO_4)_3 \cdot 8H_2O$



- Development with a rare earth company (Nippon Yttrium Co., Ltd.)
- Dedicated process line
  - All the chemicals / pure water are screened.
  - 40 tons production in 2 years = 2 tons/month
- Evaluation of raw materials and batch-by-batch screening

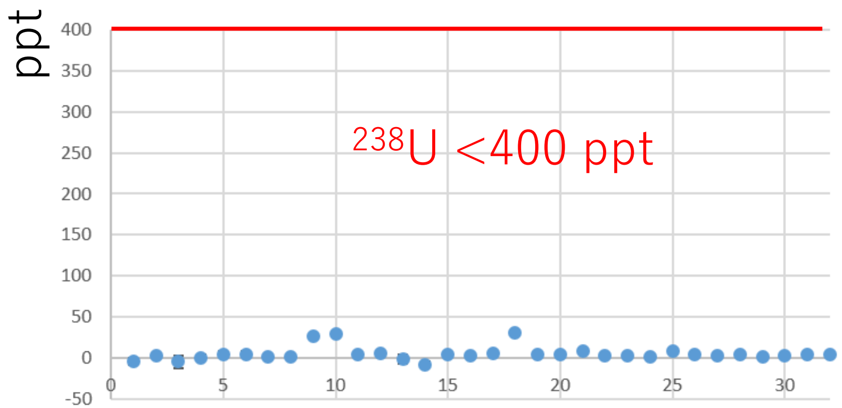
Evaluation of 40 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$

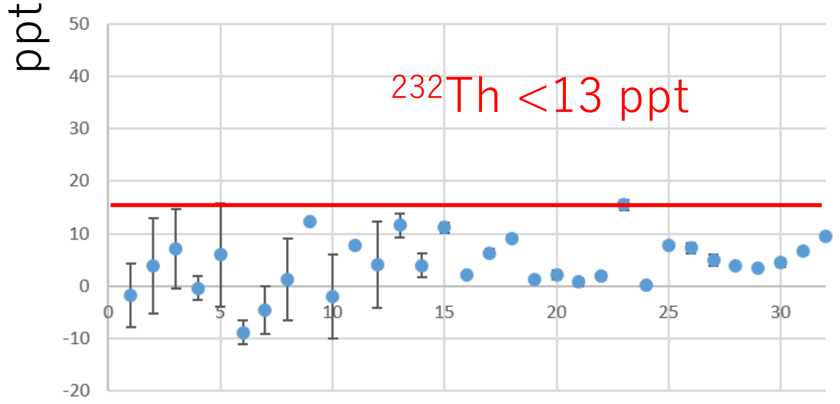
- All the ~60 batches are evaluated with **ICP-MS** and **Ge detectors**

ICP-MS: For long lifetime isotopes

Established the method of separation and extraction of U/Th from high Gd concentration solution using resin to evaluate at ppt level

PTEP 2017 11 113H01
PTEP 2019 6 063H03





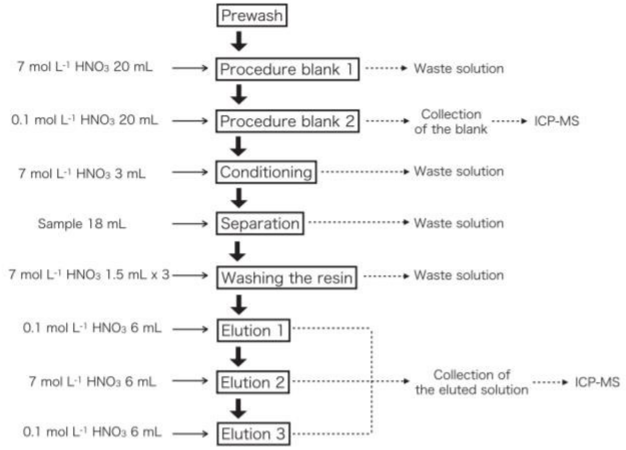
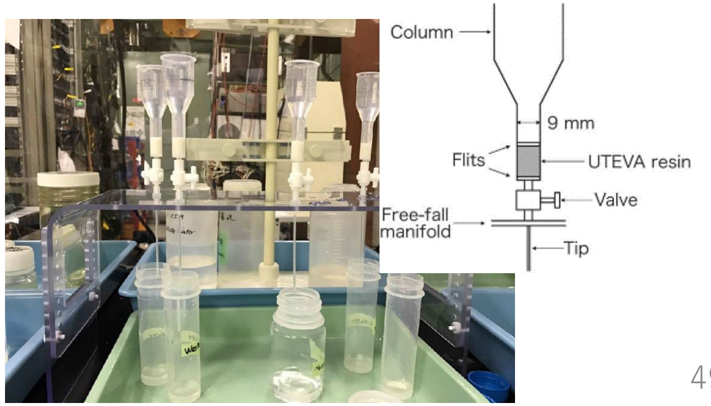


Fig. 6. Diagram of the whole procedure for the solid-phase extraction.



Evaluation of 40 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$

- All the batches are evaluated with ICP-MS and Ge detectors

Ge: For short lifetime isotopes

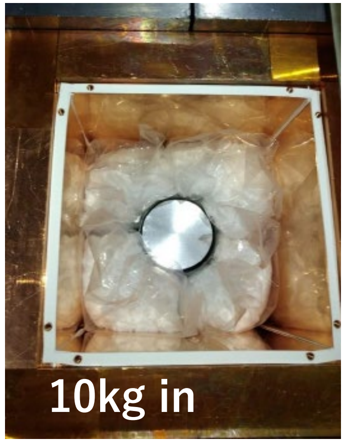
The highest sensitivity (lowest BG Ge) detectors in the world shared the work (Canfranc, Boulby, and Kamioka collaboration)

Will be submitted soon

LSC
Laboratorio Subterráneo de Canfranc

BOULBY UNDERGROUND LABORATORY

KAMIOKA OBSERVATORY



Ra-disk method

Sample	Laboratory	Detector / Method	Activity (mBq/kg, 95% c.l.)										
			^{238}U		^{232}Th		^{235}U						
			^{238}U eq.	^{226}Ra eq.	^{232}Th eq.	^{228}Th eq.	^{235}U eq.	$^{227}Ac/^{227}Th$ eq.	^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
		requirement →	<5	<0.5	<0.05	<0.05	<30	<30	-	-	-	-	-
190302	Canfranc	ge-Asterix	<9.8	<0.32	<0.35	<0.29	<0.42	<0.92	<1.6	0.26±0.1	<0.21	<0.09	<0.09
190303	Canfranc	ge-Asterix	<8.4	<0.3	<0.44	<0.29	<0.39	<0.81	<1.5	0.45±0.09	0.16±0.12	<0.08	<0.09
190304	Canfranc	HADES	<88	<7.7	<2.6	<3.3	<5.0	<9.5	<10	1.34±0.96	<1.28	-	<1.26
190305	Canfranc	ge-Asterix	<9.0	<0.34	<0.36	<0.30	<0.41	<0.90	<1.6	0.5±0.1	0.14±0.13	<0.09	<0.12
190401	Boulby	Belmont	<5.6	<0.49	<0.67	<0.46	<0.34	<1.83	<2.4	0.38±0.11	<0.34	-	<0.14
190501	Boulby	Merrybent	<12.6	<1.25	<0.92	<1.14	<0.87	13.6±2.0	<5.4	0.29±0.20	1.8±0.3	-	<0.19
	Kamioka	Lab-C Ge, Ra Disk	-	<0.42	<0.35	<0.29	-	-	-	-	-	-	-
190502	Boulby	Belmont	<5.4	<0.49	<0.95	<0.48	<0.36	<1.7	<2.8	<0.28	0.49±0.08	-	<0.10
	Kamioka	Lab-C Ge	<22.3	<0.67	<0.44	<0.29	<8	7.9±0.8	-	-	0.68±0.18	-	-
190601	Canfranc	ge-Asterix	<10.2	<0.52	<0.35	<0.41	<0.50	<1.36	<1.9	<0.16	1.25±0.14	<0.10	<0.11
	Kamioka	Lab-C Ge, Ra Disk	-	<0.32	<0.39	<0.34	-	-	-	-	-	-	-
190602	Canfranc	ge-Tobazo	<29	<0.49	<1.64	<0.82	<0.76	<1.85	<2.1	<0.21	1.64±0.20	<0.17	<0.14
	Kamioka	Lab-C Ge, Ra Disk	-	<0.28	<1.01	<0.28	-	-	-	-	-	-	-
190603	Canfranc	ge-Anayet	<30	<0.54	<1.20	<0.82	<0.67	1.3±1.3	<1.8	<0.19	1.73±0.16	<0.16	<0.14
190604	Boulby	Belmont	<9.80	<0.47	<0.61	<0.50	<0.45	<2.33	<2.45	<0.21	0.97±0.11	-	<0.08
	Kamioka	Lab-C Ge	<23.1	<0.60	<0.43	<0.26	<3.6	1.2	-	-	1.43±0.19	-	-
190606	Boulby	Merrybent	<13.1	<0.84	<0.79	<0.63	<0.37	2.6±0.6	<3.27	<0.29	1.23±0.16	-	<0.13
	Kamioka	Lab-C Ge	<13.5	1.04±0.38	<0.71	<0.82	<6.5	2.7±1.2	-	-	0.74±0.29	-	-
	Kamioka	Lab-C Ge, Ra Disk	-	<0.24	<0.71	<0.40	-	-	-	-	-	-	-
190607	Canfranc	ge-Oroel	<7.2	<0.30	<0.79	<0.42	<0.30	<0.96	<1.59	<0.18	<0.13	<0.12	<0.09
190608	Canfranc	ge-Asterix	<8.8	<0.53	<0.43	<0.35	<0.40	<0.88	<1.50	<0.14	<0.25	<0.08	<0.09
	Kamioka	Lab-C Ge	<20.4	0.99±0.30	<1.22	<0.71	<3.4	1.6	-	-	<0.45	-	-
	Kamioka	Lab-C Ge, Ra Disk	-	<0.49	<0.43	<0.55	-	-	-	-	-	-	-
190702	Canfranc	ge-Oroel	<11.0	<0.45	<1.11	<0.50	<0.37	2.4±0.9	<1.5	<0.20	0.23±0.13	<0.12	<0.11
	Kamioka	Lab-C Ge	<11.4	<0.55	<1.09	<0.30	<3.0	<1.5	-	-	<0.35	-	-
190703	Canfranc	ge-Asterix	<8.4	<0.35	<0.51	<0.50	<0.45	1.8±1.0	<1.7	<0.20	0.51±0.13	<0.10	<0.10
190704	Boulby	Belmont	<9.8	<0.44	<0.66	<0.75	<0.29	<1.39	<2.01	<0.25	<0.18	-	<0.10
190705	Boulby	Merrybent	5.9±2.6	<0.50	<0.50	<0.57	<0.32	<1.31	<2.20	<0.19	1.6±0.1	-	<0.08
190706	Boulby	Belmont	<9.5	<0.45	<0.66	0.53±0.12	<0.28	<1.32	<2.09	<0.25	<0.25	-	<0.13
	Kamioka	Lab-C Ge	<7.3	<0.64	<0.39	<0.59	<1.76	<0.83	<1.7	-	<0.15	-	<0.20
190801	Canfranc	ge-Anayet	<28	0.39±0.32	<1.5	<0.77	<0.80	<1.17	<1.44	<0.18	2.7±0.2	<0.23	<0.18
190802	Boulby	Merrybent	<8.44	<0.57	<0.56	<0.68	<0.48	<1.18	<2.54	<0.17	4.71±0.20	-	<0.09
190803	Canfranc	ge-Asterix	<7	<0.31	0.39±0.21	0.55±0.22	<0.36	<0.74	<1.4	<0.09	3.5±0.1	<0.08	<0.07
190804	Boulby	Belmont	<11	<0.46	0.67±0.21	<0.67	<0.38	<1.98	<2.57	<0.20	4.60±0.24	-	<0.10
190805	Canfranc	ge-Oroel	<9.3	<0.52	0.53±0.44	0.57±0.40	<0.44	<0.98	<1.18	<0.10	9.44±0.10	<0.10	<0.09
	Kamioka	IPMU-P	<103	<1.6	<3.2	<4.9	<16	<7.0	<18	-	8.83±0.82	-	<1.2
190806	Boulby	Merrybent	<8.09	<0.43	0.49±0.11	1.27±0.13	<0.26	<1.23	<1.78	<0.14	9.35±0.22	-	<0.07
	Kamioka	IPMU-N	<93	<3.9	<3.3	<2.6	<19	<6.4	<65	-	5.5±0.9	-	<1.4
190901	Canfranc	ge-Asterix	<8.6	<0.30	0.42±0.27	0.37±0.27	<0.46	<1.20	<1.47	<0.15	4.85±0.12	<0.10	<0.13
	Kamioka	IPMU-P	<110	<2.3	<2.9	<2.1	<14.9	<12.2	<27	-	5.6±0.7	-	<1.1
190902	Boulby	Belmont	<5.52	<0.26	0.53±0.10	0.63±0.09	<0.33	<1.22	<1.32	<0.10	8.78±0.18	-	<0.05
	Kamioka	IPMU-N	<71	<4.9	<3.2	<2.5	<19	<8.0	<46	-	6.4±0.9	-	<1.4
190903	Kamioka	IPMU-N	<69	<6.3	<4.0	<2.4	<17.6	<5.3	<32	-	5.4±0.8	-	<1.0
190904	Boulby	Belmont	<10.80	<0.49	0.69±0.22	0.65±0.15	<0.52	<2.12	<2.79	<0.20	6.41±0.30	-	<0.09
	Kamioka	IPMU-N	<70	4.6±1.6	<3.3	<2.4	<18	<5	34±16	-	5.1±0.8	-	<2.2
190905	Kamioka	Lab-C Ge	<6.7	<0.16	0.7±0.2	0.7±0.2	8.8±1.9	<1.0	<1.4	-	6.6±0.2	-	<0.1
190906	Kamioka	Lab-C Ge	<7.0	<0.19	1.09±0.23	0.45±0.14	6.0±2.0	<0.53	<1.1	-	5.92±0.21	-	<0.10
191001	Kamioka	Lab-C Ge	<5.2	<0.26	1.62±0.24	0.55±0.13	4.6±1.6	<0.45	<1.13	-	5.57±0.17	-	0.13±0.08
200101	Kamioka	IPMU-N	<87	<2.8	<4.0	<2.5	<18	<4.5	<67	-	5.2±0.9	-	<1.2
200102	Kamioka	IPMU-P	<122	<2.5	<3.1	<3.3	<16	<7.9	<25	-	7.0±0.8	-	<0.98
200103	Kamioka	IPMU-N	<114	<2.4	<7.7	<2.4	<17	<4.1	<19	-	<0.91	-	<1.0
200104	Kamioka	IPMU-P	<95.1	<2.8	<3.0	<2.8	<15	<9.0	<31	-	<0.82	-	<0.64

Spectral shape fitting

For each DSNB model, the obtained energy spectra were fitted with expected BG above 15.5MeV region.

- Side-band regions separated by Cherenkov angles were fitted simultaneously.

  Low angle region:

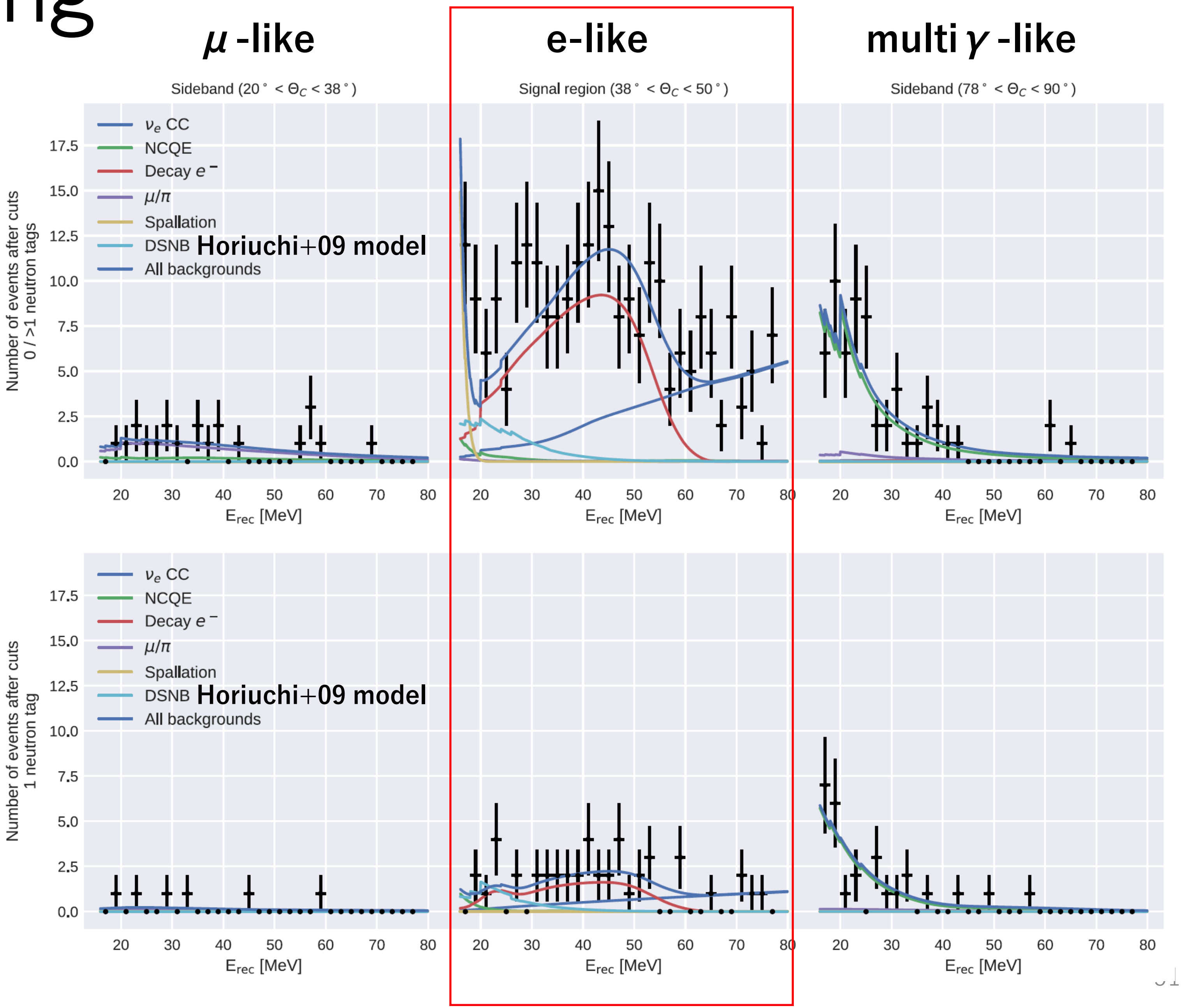
  Atmospheric backgrounds involving visible □ and p.

  High angle region:

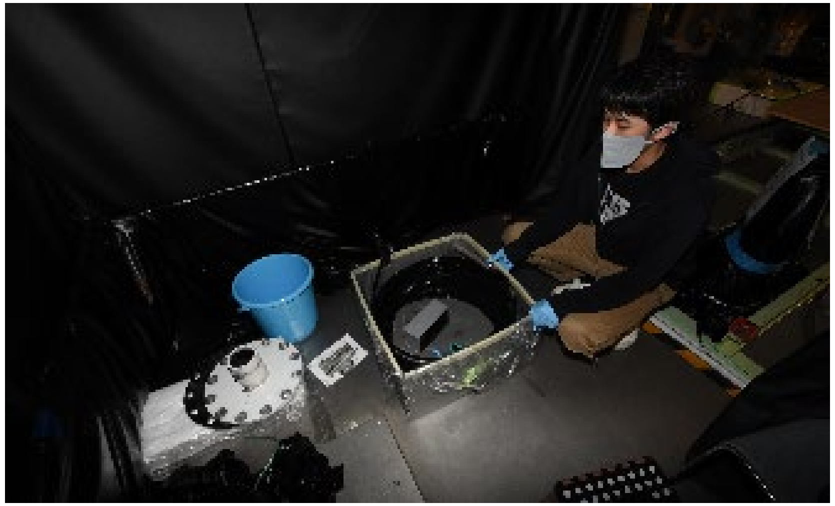
  NCQE events with multiple γ-rays.

"IBD-like" events (exactly one identified neutron) and "non-IBD-like" events are also separated.

- Due to the low efficiencies of the neutron tagging cuts, the non-IBD-like events still contain a sizable signal.

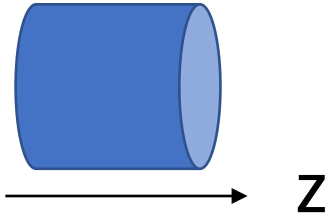


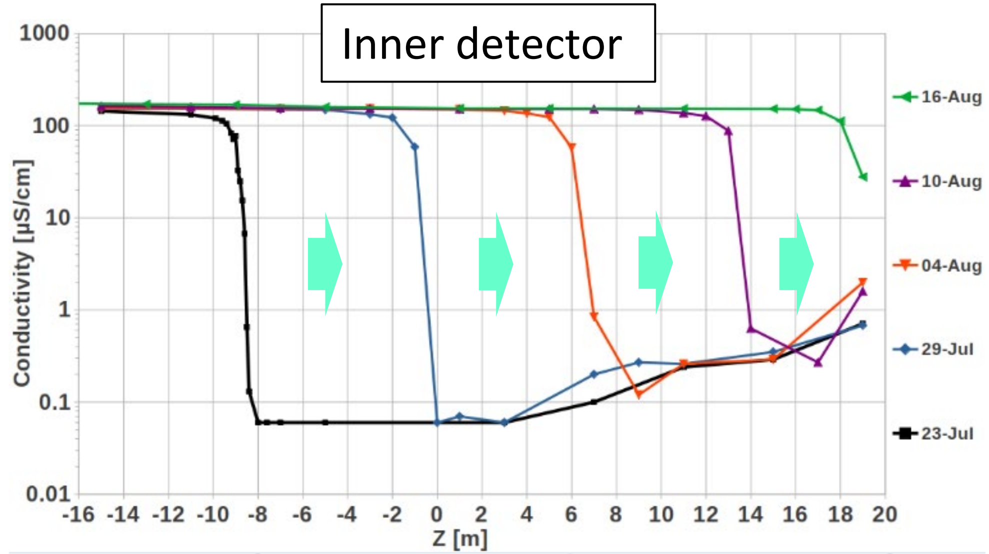
Gd concentration check during the loading

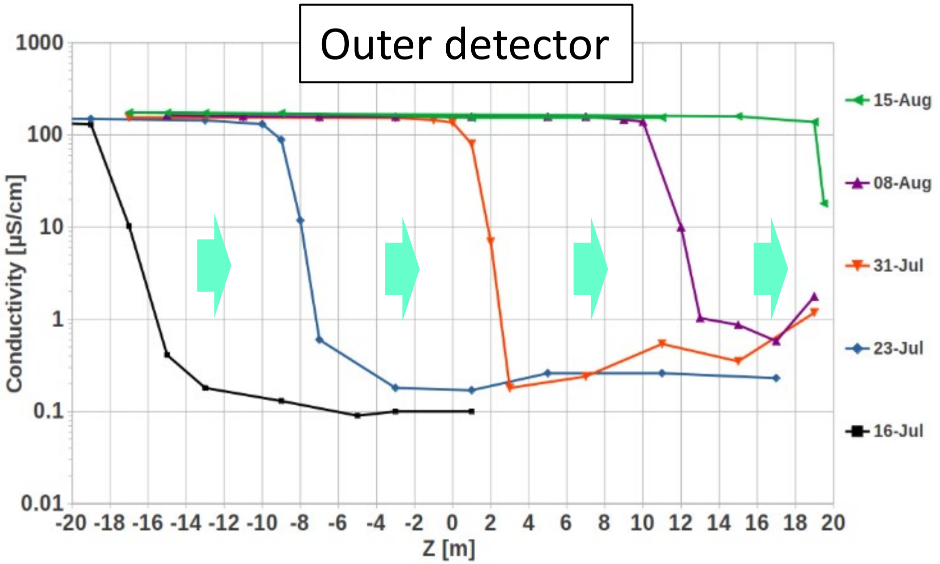


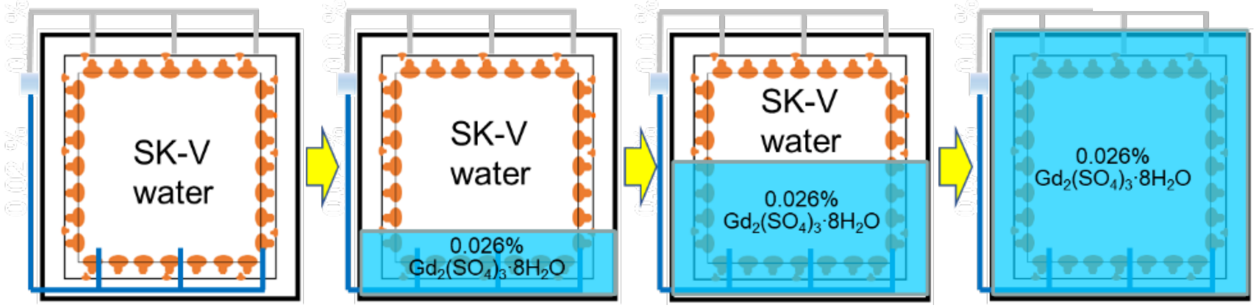
Sampled water directly from various positions in the tank, and its conductivity was measured

Aug.15
Aug.10
Aug. 4
Jul.29
Jul. 23





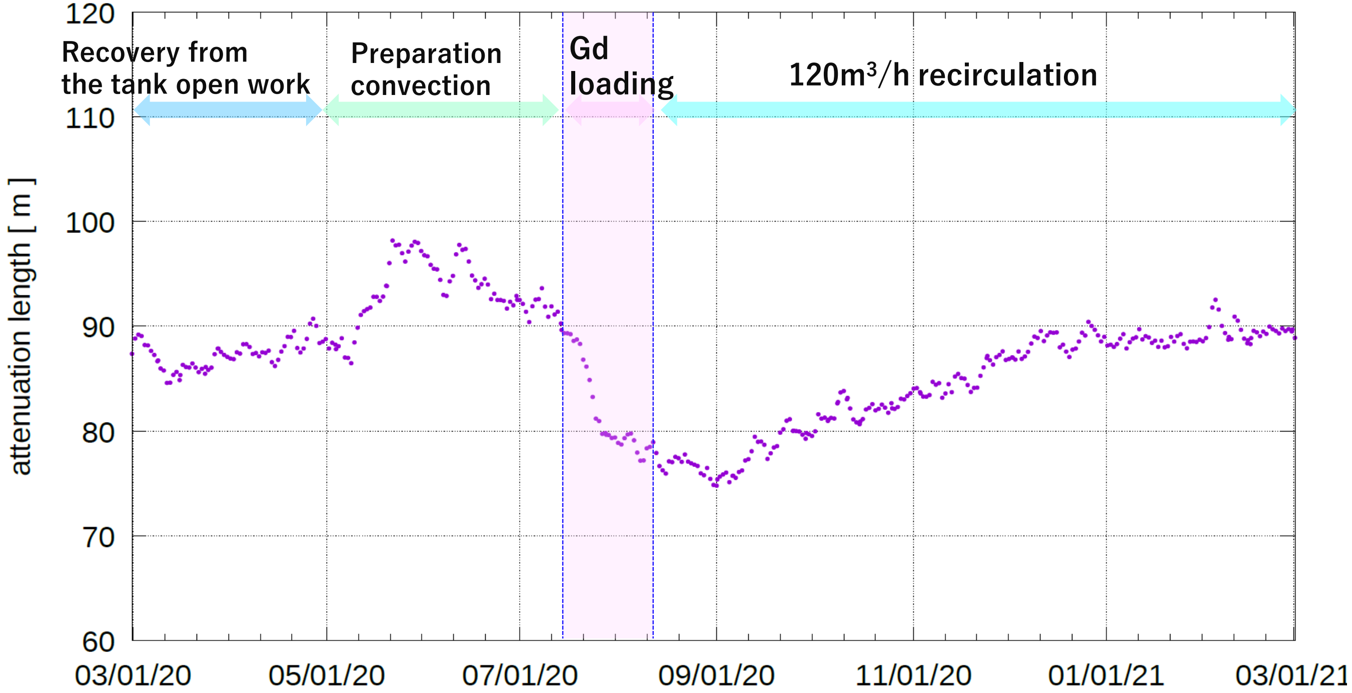




Confirmed Gd built up from the bottom of the tank

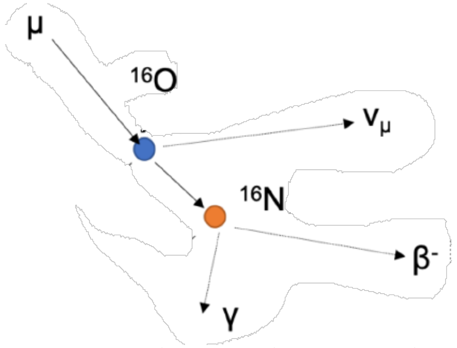
Water transparency and energy scale

- The same level of transparency as that of pure water phase



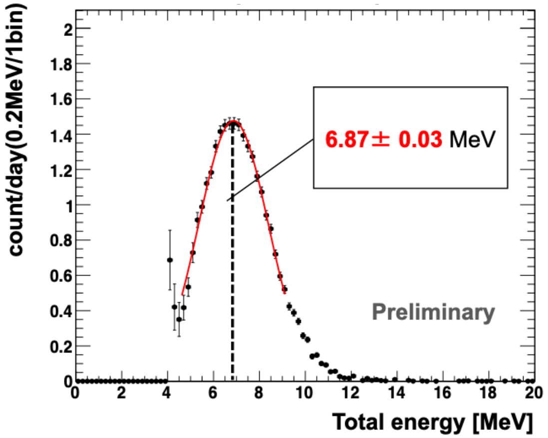
There is no significant change in water transparency or energy scale before and after the Gd-loading, allowing for the same physics studies to date.

- Energy scale compared between SK-IV and SK-VI using ^{16}N decay events from cosmic μ captured ^{16}O

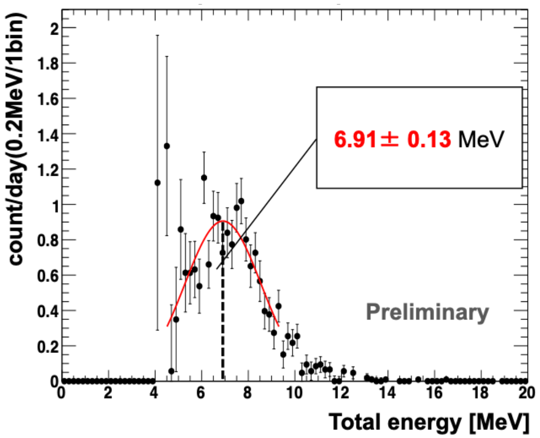


$^{16}N \rightarrow \beta^-$(Q 4.3MeV) + γ(6.1MeV) BR: 66.2%
β^-(Q 10.4MeV) BR:28.0%
β^-(Q 3.3MeV) + γ(7.1MeV) BR: 4.8%

SK-IV 2970days (before Gd)



SK-VI 106days (after Gd)



N.B. Cut efficiencies are not optimized yet (especially for SK-VI)